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EXPANSIVE CEMENT CONCRETES FOR NAVAL CONSTRUCTION

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13. ABSTRACT

Expansion and subsequent shrinkage characteristics of shrinkage-compensating concrete were determined in mesh-reinforced prisms as well as in "standard" Rubin bars. The maximum aggregate size was 3/8 inch. The specimens were cured in fog for 14 days and then subjected to drying in either 25% or 50% relative humidity (both at 73°F). Although mixes were made with several different cement contents, most of the specimens were made with 7.5 sacks of cement per cubic yard. For comparison purposes, similar mixes were made with portland cement. The specimens of shrinkage-compensating concrete showed 20 percent less shrinkage strains at 50% RH than those of portland cement concrete. The effects of the amount of restraints on expansion and shrinkage were also determined. Compressive strengths and Young's moduli of shrinkage-compensating concrete compared favorably or exceeded similar values for portland cement concrete. Research plans for FY73 are delineated.

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BACKGROUND

The industrial manufacture of portland cement involves the use of raw materials containing lime (CaO), silica (SiO_2), alumina (Al_2O_3), and iron (Fe_2O_3).[1,2] The raw materials are pulverized and properly proportioned to obtain the desired chemical composition. The ingredients are then heated at 2,600°F to 3,000°F to form portland cement clinker. The clinker is later pulverized to form portland cement. The products formed are tricalcium silicates (C_3S), dicalcium silicates (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF). The setting of C_3S and C_2S is fairly slow, but setting of C_3A is very rapid. There is not much C_3A in modern portland cements, but the finer nature of these cements makes flash setting of C_3A more probable. It was found, however, that addition of small amounts of gypsum prevents flash setting of C_3A. For this reason, very carefully controlled amounts ($\pm 0.10\%$) of gypsum are added to the cement during the final pulverizing step. The gypsum ($CaSO_4 \cdot 2H_2O$) combines with the C_3A to form a needle-like insoluble compound called calcium sulfoaluminate ($C_6A\bar{S}_3 \cdot 32H_2O$). This product, called ettringite because it resembles the natural mineral ettringite, occupies a fairly large volume, and an excess of it could result in damaging expansions after the cement has hardened. Under normal conditions the small amount of ettringite formed by the addition of a slight amount of gypsum to prevent flash setting does not result in damaging expansions. However, the recognition of the potential expansions resulting from formation of ettringite led to development of expansive cements as we now know them.

This technical note is an interim report on a continuing research study being conducted at the Naval Civil Engineering Laboratory (NCEL), the first efforts of which are directed toward use of expansive cement concretes in thin-shell construction.

INTRODUCTION

The development of expansive cements has been documented by several authors[3,4,5] and by Technical Committee 223 of the American Concrete Institute (ACI).[6] The following remarks regarding this development were taken from these references.

The motivating stimulus behind development of expansive cements was twofold: (1) Elimination of shrinkage cracking, and (2) inducement of relatively high levels of precompression in the concrete, much as is

done by mechanical prestressing. The twofold objective resulted in development of (1) a shrinkage-compensating expansive cement, and (2) a self-stressing expansive cement. The principal difference between the two classes of expansive cements is the amount of expansive component provided for reaction with portland cement ingredients to form ettringite, the expansion producer.

Purposeful research and development on the use of ettringite to produce expansions intended to overcome the effects of shrinkage and to self-stress concrete began in France in the mid-1930's. An expansive cement for repairs and for waterproofing as well as for self-stressing was developed in Russia by Mikhailov. Studies by Klein, et al, at the University of California (Berkeley) led to the development of commercial expansive cements.

ACI Committee 223 lists the following definitions pertinent to expansive cements and concretes:[6]

1. Expansive cement - A cement which when mixed with water forms a paste that, during and after setting and hardening, increases significantly in volume.

2. Expansive cement, Type K - A mixture of portland cement compounds, anhydrous calcium sulfoaluminate, calcium sulfate and lime. The anhydrous calcium sulfoaluminate is a component of a separately burned clinker that is interground with portland clinker or blended with portland cement or, alternately, it may be formed simultaneously with the portland clinker compounds during the burning process.

3. Expansive cement, Type M - Either a mixture of portland cement, calcium aluminate cement and calcium sulfate, or an interground product made with portland cement clinker, calcium aluminate clinker and calcium sulfate.

4. Expansive cement, Type S - A portland cement containing a large C_3A content and modified by an excess of calcium sulfate above the usual amount found in other portland cements.

5. Expansive cement concrete - A concrete made with Type K, Type M, or Type S expansive cement.

6. Shrinkage-compensating concrete - An expansive cement concrete in which expansion, if restrained, induces compressive stresses which approximately offset tensile stresses in the concrete induced by drying shrinkage. (The level of precompression in shrinkage-compensating concrete is in the range of 15 psi to 100 psi.)

7. Self-stressing concrete - An expansive cement concrete in which expansion, if restrained, induces compressive stresses of a high enough magnitude to result in significant compression in the concrete after drying shrinkage has occurred. (The level of precompression in self-stressing concrete is in the range of 300 psi to 1,000 psi.)

8. Ettringite - The phase formed during the hydration of expansive cements which is the source of the expansive force. It is comparable to the natural mineral of the same name.

FACTORS AFFECTING EXPANSION OF CEMENTS

Purposeful expansion is one of the features distinguishing expansive cements from portland cements. As shown by other researchers, the amount of achievable expansion for a given cement is dependent upon the factors listed below.

Chemical Composition and Fineness

Rate of expansion is proportional to the amount of readily hydratable aluminates so long as $CaSO_4$ is available.[6] The aluminates may be $C_4A_3\bar{S}$ (Type K), calcium aluminate cement (Type M), or C_3A (Type S). As the fineness of an expansive cement increases, the amount of expansion decreases. The increase in fineness accelerates the formation of ettringite. If the bulk of expansion takes place before the concrete has achieved sufficient strength, it will be wasted; on the other hand, if the bulk of the expansion occurs after the concrete has reached a relatively high strength level, internal damage may result from the expansions. A Blaine fineness of about 2800 seems optimum.[7]

Amount of Expansive Material

Generally speaking, the more of the expansive material that is present, the more will be the expansion. The essential expansion ingredients can be proportioned into all types of expansive cements to cover the entire range of expansions. The commercially available Type K and Type S shrinkage-compensating cements are proportioned to produce relatively low expansions. The Type K cements contain from 10% to 15% expansive components having from 25% to 50% calculated $C_4A_3\bar{S}$ (calcium sulfoaluminate). Laboratory studies on Type K self-stressing cements have utilized contents of expansive component from 10% to 50%. Expansion of self-stressing cements is related to amount of expansive component but not proportionately. Polivka and Bertero[8] have recommended that the influence of amount of expansive component in self-stressing concretes be evaluated on the specific type of concrete to be used.

Water Cement Ratio (W/C)

Generally speaking, the lower the W/C, the higher the expansion; however, changes in W/C also affect relative proportions of other ingredients.[6] For instance, concretes with the same cement content can be made with a range of values of W/C. In this case, all the concretes would have the same potential for expansion (cement content) but the more pervious, higher slump concretes (higher W/C) will take up curing water more readily and therefore will expand somewhat more (see below on effects of curing on expansion).

Curing

The requirements for proper curing of expansive cement concretes are more stringent than for portland cement concrete.[6] The formation of the strength-producing calcium silicate hydrates (C_3S and C_2S) and the expansion-producing ettringite are affected differently by curing temperature and by availability of water. Inadequate curing can substantially reduce the level of expansion. All expansive cement concretes expand significantly more when cured under water or in a moist room than they do when cured in an environment in which water is not available to the concrete. Curing under a polyethylene sheet greatly reduces expansions when compared to water curing. Steam-cured expansive concretes expand only about 80% as much as when water-cured. Lightweight concretes, in which the highly absorptive lightweight aggregates give off water and thus provide a form of internal curing, have been shown to have improved expansion characteristics, especially in larger sections where a moisture gradient is usually established.[9] The presence of internal water also reduces the potentially damaging effects of differential expansions in the larger sections. Results of tests to determine the effects of curing temperature on expansion are conflicting. More research is needed.

Size and Shape of Member

Other things being equal, expansion decreases as the size of the member increases. In addition, the exterior can expand at a different rate from the interior of large moist-cured members, and when these differences are significant, mechanical properties are adversely affected.[6] As stated above, internal curing achieved by using lightweight aggregate tends to alleviate these differentials. The influence of shape of member has not yet been determined.

Restraint

Successful utilization of any of the expansive cement concretes depends upon the amount and type of resistance to the expansion of the concrete. An expansive cement concrete in which no resistance is provided to the expansion shows greatly reduced mechanical properties. In the

language of the expansive cement industry the resistance to expansion is called "restraint". Restraint can be either external, as in the case of rigid framework, or internal in the form of reinforcing steel or mesh.[5,6,10] Some degree of restraint can also be provided by such forces as subgrade friction and by abutting structures. In the case of reinforcing steel or mesh, the developing bond strength provides the necessary restraint to expansion. Resistance to the expansion places the steel in tension and this in turn places the concrete in compression, much as in prestressed concrete. Most tests have been made on specimens using uniaxial (longitudinal) restraint. Generally speaking, the more the restraint (% of reinforcement), the less the measured expansion and the more the induced compression in the concrete. However, since the expansion potential for a given concrete is the same regardless of degree of restraint, an increase in longitudinal restraint (uniaxial) might cause lateral expansions large enough to adversely affect the mechanical properties.[10] For this reason, there is an optimum amount of uniaxial restraint for a given expansive cement concrete which will produce adequate prestress forces, minimum lateral expansions, and best mechanical properties. Most field installations of shrinkage-compensating concretes have utilized successfully the amount, kind, and position of reinforcement required for the given structure. Some tests made with biaxial restraint have shown improvements in uniformity of expansion and in mechanical properties. Self-stressing concretes, due to their higher level of expansion, may require triaxial restraint, although successful tests have been made with biaxial restraint.

Mixing Time

Increasing mixing time decreases the expansion of a given expansive cement concrete.[6] Mixing accelerates formation of ettringite and thus depletes its availability for later expansion. Continued mixing also increases the water required to obtain a given slump.

Use of Admixtures

Most of the admixtures used successfully with expansive cement concretes have been water-reducing retarders (lignins and sodium gluconate base).[6] In warm weather rather large doses have been used to delay initial setting time. Use of admixtures in winter did not create any difficulties. All expansive cement concretes used in areas where durability must be considered have incorporated air entrainment.

Type and Size of Aggregate

Both rate and amount of expansion are affected by type of aggregate.[6,9] Of three types tested, crushed granite, river gravel, and expanded shale, the expanded shale concrete expanded the most and the river gravel the least. Data on the effects of aggregate size are limited. For a given

workability, yield, and W/C, an increase in aggregate size is accompanied by a decrease in cement content. This change in cement content may cause a greater change in expansion than would the change in aggregate size.

Age of Expansive Cement

The length of storage of expansive cement after manufacture tends to reduce slightly the restrained expansion. The best practice is to keep the cement in sealed drums, away from exposure to air.[6]

PROPERTIES OF EXPANSIVE CEMENT CONCRETES

The following statements regarding properties of expansive cement concretes are based on previous research data obtained by other researchers together with observations made during and after field installations of full-size structures.[5,6,11,12]

Shrinkage-Compensating Concretes

Workability.[6] The workability of concretes made with Type K, Type S, and Type M shrinkage-compensating cements is the same as for portland cement concrete of equal slump. Type K cement seems to require slightly more water for the same slump but the additional water probably combines with the expansive component and thus does not appear to adversely affect the other properties (W/C, strength, etc.).

Bleeding.[6] All three expansive cements have shown a consistent decrease in bleeding compared with similar portland cement concretes. In some cases there has been no bleeding at all with expansive cement concretes.

Setting time.[6] Setting times of all three shrinkage-compensating cements are comparable to Type I portland cement.

Unit weight and yield.[6] Shrinkage-compensating concretes have about the same unit weight and yield as does portland cement concrete, other things being equal.

Strengths.[6,11] Shrinkage-compensating concretes develop compressive, tensile, and flexural strengths equivalent in rate and magnitude to concretes made with Type I and Type II portland cements.

Modulus of elasticity (E).[6] Moduli of elasticity, static and dynamic, of shrinkage-compensating concretes are comparable to those in portland cement concretes.

Shrinkage and creep.[6] Shrinkage of shrinkage-compensating concrete is about the same as in portland cement concrete. No data are available on creep.

Bond strength.[6] Very few comparative bond tests have been made. Those tests which have been made showed that bond strengths of concrete made with Type K shrinkage-compensating cement were equal to or greater than those in the companion portland cement concrete.

Coefficient of thermal expansion.[6] Few tests have been made, but those show a coefficient similar to portland cement concrete.

Resistance to freezing and thawing.[12] Shrinkage-compensating concretes can be made resistant to damage from freezing and thawing with proper air entrainment and with relatively high cement content.

Resistance to de-icer scaling.[11,12] Shrinkage-compensating concretes showed resistance to de-icer scaling equal to or greater than comparable portland cement concrete.

Resistance to sulfate attack.[6,11] Very few tests have been conducted. Results are contradictory, with some showing favorable resistance of shrinkage-compensating concretes to sulfate attack and some unfavorable.

Abrasion resistance.[6] Shrinkage-compensating concrete made with Type K cement was found to have abrasion resistance superior to that of portland cement concrete.

Self-Stressing Concretes

Workability.[6] Most reports of experiments with self-stressing concretes indicate rapid stiffening, particularly at low water-cement ratios.

Bleeding.[6] Self-stressing concretes show no bleeding.

Setting time.[6] Self-stressing concretes show more rapid setting than portland cement concrete. For example, Type M cement has been known to reach an initial set in 2 minutes and a final set in 6 minutes. A set-retarding admixture will correct this and seems to have no effect on the expansive characteristics of the cement.

Unit weight and yield.[6] Specific gravity of Type K self-stressing cement is 3.0, compared to 3.15 for portland cement, and this difference should be taken into consideration when calculating unit weight and yield.

Compressive strength.[6,8,9,10] The compressive strength of self-stressing concrete is inversely proportional to the amount of expansion, and the amount of expansion is inversely related to the amount of restraint. Within reasonable limits, then, the more the restraint, the higher the strength. The type of restraint also affects compressive strength of self-stressing concrete; triaxial restraint provides up to 25% higher compressive strength than uniaxial restraint. Generally speaking, the compressive strengths of self-stressed concretes are lower than comparable portland cement concrete, if there is a real way to compare the two. High strength self-stressing concrete can be made when careful consideration is given to all the variables involved. More research will point the way to greater strengths.

Shrinkage and creep.[6,9] As in mechanically prestressed concrete, shrinkage and creep must be considered. Tests on structural elements made with Type K self-stressing cement show stress losses in steel and concrete due to creep and shrinkage about equal to those observed in conventional prestressed concrete. Shrinkage of lightweight self-stressed concrete has been shown to be less than in conventional concrete, probably due to the storage and later release of water in the lightweight aggregate.

Modulus of elasticity (E).[6] As with compressive strength, the E of self-stressing concrete is inversely related to the amount of expansion and directly related to the amount of restraint. E increases with increasing age and with increasing cement contents. Triaxial restraint provides somewhat higher E values than uniaxial restraint. Generally speaking, fairly high E values for self-stressing concretes can be obtained by careful design and control, but they are somewhat lower than for portland cement concrete if a true comparison can be made.

Bond strength.[6] High bond strengths can be obtained if adequate lateral restraint is provided.

Resistance to freezing and thawing and de-icing salts.[6] Specimens of self-stressing concrete with higher amounts of restraint showed greater resistance to freezing and thawing and to de-icer scaling than did specimens with lower amounts of restraint. None of the self-stressing concretes equaled the resistance of concrete made with Type V portland cement.

POTENTIAL NAVAL APPLICATIONS

Shrinkage-Compensating Concretes

Thin-shell roofs and thin precast roof panels. Shrinkage cracking of thin-shell structures (1 in. to 2 in. thick) is a continuing problem, both from the standpoint of potential water leaks into the building and

from potential corrosion of reinforcing steel in concrete. The relatively small compressive stresses induced in the shell (or panel) by use of shrinkage-compensating concrete should offset the tensile stresses resulting from drying shrinkage and tend to maintain the shell in a state of compression. The goal is to obtain the highest Young's modulus possible with optimum economic combinations of mesh reinforcement and cement content.

Precast wall panels. It was found at the Portland Cement Association Laboratories that precast concrete wall panels made with Type K shrinkage-compensating cement have mechanical properties equal to those of similar panels made with Type I portland cement.[13] The flexural cracking loads of the Type K panels were about 15% higher than those of the Type I panels. After drying (shrinking) for 180 days, the Type K panels still had 10 psi to 30 psi precompression in the concrete. Shrinkage stresses in the Type I panels after the 180 days drying period were 30 psi to 50 psi (tensile).

Building elements. Shrinkage-compensating concretes have already been used successfully in pan joists, waffle slabs, columns, floor slabs, tilt-up walls, cantilevers, and tee sections.[6] The product has also been used in pretensioned and post-tensioned prestressed concrete. In all these types of building elements the induced precompression serves to counteract the tensile stresses from shrinkage and from a drop in temperature.

Airfield pavement slabs. There is a potential saving in joint spacing when shrinkage-compensating concrete is used in reinforced pavement slabs, because the precompression in the concrete tends to overcome shrinkage stresses, temperature stresses, and stresses due to friction between pavement and subgrade.[6] In 1969 a taxiway 75 feet wide and about 5,200 feet long was constructed of shrinkage-compensating concrete at Love Field, Dallas, Texas. The taxiway was built in 3 lanes, each 25 feet wide and 14 inches thick. Contraction joints were sawed at 125-foot intervals and no expansion joints were provided. As of March 1972, only three insignificant cracks had been found, and there have been no problems in connection with the sawed joints. The taxiway has very heavy use and is subjected to severe temperature changes. Previous taxiways constructed of portland cement concrete, with contraction joints spaced at 50 feet, developed transverse cracks about half-way between joints. A second taxiway, 16 inches thick, is currently being constructed with shrinkage-compensating concrete.

Ferro-Cement. Expansive concrete should prevent the development of shrinkage cracks in ferro-cement boats, which the Vietnamese recently reported while visiting NCEL. Prevention of cracking will also minimize corrosion of the mesh and other reinforcing in ferro-cement mortars.

Pipe. By using single or multiple layers of wire mesh or high tensile steel reinforcement, prefabricated pipe can probably be made automatically. One approach to the problem of forming is to use a thin outer shell of steel or plastic to provide triaxial restraint. The degree of outer surface restraint (thickness of steel shell) would depend upon the amount of prestress desired.[5,6,14]

Composite elements. Self-stressed precast elements could be used in combination with cast-in-place shrinkage-compensating concrete. An example is a tee section formed by combining a precast self-stressed girder (as the stem) with a slab of shrinkage-compensating concrete.[14,15]

Slabs, plates, shells, wall panels. In thin slabs for floors and roofs, in folded plates, in thin shells, and in wall panels the required amount of prestress and reinforcement are not high. Such elements, therefore, could be fabricated economically by self-stressing.[14] A four-sided hyperbolic parabaloid was constructed of self-stressing concrete and the net expansion after drying shrinkage caused a tensile stress in the steel of 94,000 psi and a compressive stress in the concrete of 420 psi.[5,6] The amount of prestress is sufficient to prevent cracking even under high loads. The edge beams of thin shells could be prestressed by self-stressing concrete, thus eliminating the cost of the mechanical prestressing.

Water tanks. Prestressed water tanks could be made with self-stressing concrete, thus eliminating the costs connected with mechanical prestressing.

Columns. Spirally reinforced columns of self-stressed concrete have been made successfully in the laboratory. In addition, a composite steel-concrete column could be made by using thin tubes of high-strength steel filled with self-stressing concrete. The steel tube would provide the necessary restraint.[14]

Ferro-Cement. Self-stressing mortar should tend to compress very tightly this very thin heavily reinforced type of construction, when sufficient triaxial restraint is provided. A high level of induced compression should greatly increase the flexural and impact strength as well as increase durability.

Structural system units. For construction of precast buildings, such as in Habitat '67[16] in Montreal and in the Hilton Palicio del Rio Hotel[17] in San Antonio, box-type units containing partitions and floor slabs can be fabricated with self-stressing concrete.[14] The box units are being prefabricated into rooms or dwellings and completely furnished prior to being lifted into place in the structure. In Richmond, California,

Stressed-Structures, Inc. has built (1968) a 24-unit, 6-story apartment house using factory-cast sections of self-stressed concrete.[18] Two 11 ft by 36 ft concrete sections were formed for each three-bedroom apartment. Each section was precast as a three-sided monolithic unit with walls 2 in. thick. The pre-wired and pre-plumbed sections were painted and cabinets and hardware were installed before being taken to the job site. At the job site they were placed in position in the structure and secured. This structure is the pilot structure for the industrial use of self-stressing cement and, for that reason, will be watched very closely.

In connection with proposed off-shore airfield facilities, self-stressing concrete could be used to prestress deck sections as well as for supporting units. In addition, the pavement slabs could be made with shrinkage-compensating concrete to lengthen joint spacing and greatly reduce cracking. Cracking will be a serious problem in such an installation because of the presence of salt-laden spray which can find its way through cracks to the reinforcing steel (and prestressing steel) embedded in the concrete. It is well known that salts create a critical environment for steel corrosion.

RESEARCH BEING CONDUCTED AT NCEL

The research program at NCEL is designed to determine the efficacy of expansive cement concretes for Naval construction and, if the product is worthwhile and cost-effective, to enable specification, design, and construction of thin-shell and ferro-cement structures. During the investigation, consideration is also being given to uses of expansive cement concretes in other types of Naval construction. Listed below are the major factors being investigated.

- Compressive strengths of concretes made with different cement contents
- Young's modulus of concretes made with different cement contents
- Amount of expansion to be expected with different cement contents
- Effects of different amounts of restraint on expansion
- Expansion of test specimens of different sizes
- Shrinkage effects in different drying environments
- Effects of curing time on amount of expansion
- Bond strength of expansive cement concretes
- Creep of expansive cement concretes
- Effects of air-entrainment on expansion
- Effects of type and weight of aggregate on expansion
- Effects of temperature on expansion and subsequent shrinkage

It is hoped that, in cooperation with a field activity planning pertinent construction, NCEL can furnish mix design, mixing, casting, finishing, and curing details to enable the structure to be made with expansive concrete.

RESEARCH CONDUCTED AT NCEL DURING FY-72

Test Specimens

In order to obtain test data comparable to those of other investigators, a series of length change tests were made on prismatic specimens nominally 3 inches square and 10 inches long, cast in molds conforming to ASTM C490-70. For restrained specimens, the molds were modified to take a threaded mild steel rod 3/16-inch in diameter (nominal) along the central longitudinal axis. Utilization of these restrained prisms was originated several years ago by Mr. F. H. Rubin and hence have come to be known as "Rubin bars". A Rubin mold with threaded bar in-place is shown in Figure 1.

To simulate concrete thin shells, prismatic test specimens 5 inches wide and 12 inches long were made in thicknesses of 1 inch, 2 inches, and 4 inches. An example of each prism size is shown in Figure 2. The prisms were reinforced with galvanized welded wire fabric of the following spacing and wire sizes: 2 inch by 2 inch, No. 14 and No. 12 and 1 inch by 1 inch, No. 14 and No. 12. Examples of placement of the fabric with respect to the forms is shown in Figures 3, 4 and 5. Several different percentages of reinforcement were obtainable, as indicated in Table 1. Computation of reinforcement percentage was based on the total cross-sectional area of the horizontal wires viewed from either end. The vertical wires completing the fabric were not considered in computing the steel percentage. In this report, reinforcement is designated by a lower case p followed by a percentage, e.g. p=0.19%.

Also visible in Figure 3, Figure 4, and Figure 5 are the screws which serve as reference points for measurement of length changes with a mechanical strain gage. The reference screws are 5 inches apart.

Aggregates

During FY-72 all expansive cement concrete was made with river gravel and sand (Santa Clara River) having a maximum size of 3/8 inch.

Expansive Cement Concrete Mixes

Research in FY72 concentrated on shrinkage-compensating expansive cement available commercially as "Chemcomp Cement" (Type K). Mixes were made over a wide range of cement contents (590 to 1,330 pounds per cubic yard) and water-cement ratios (0.376 to 0.596 by weight), both with and without entrained air. For comparison purposes, a few mixes were made with portland Type II cements. In this report the concrete mixes are designated by the number of equivalent sacks per cubic yard followed by the type of cement used, e.g. 7.5 SCA means 7.5 sacks per cubic yard, shrinkage-compensating cement, air entrained. Mixes of portland cement concrete are designated in the same manner, e.g. 7.5 PC (7.5 sacks per cubic yard, portland cement). The vast majority of the mixes of

shrinkage-compensating concrete were made with 7.5 sacks (705 pounds) of cement per cubic yard because this mix is typical of those being used in the Los Angeles area for structural purposes (other than slabs-on-grade).

Concrete Mixing Procedure

To simulate the average mixing and hauling time of truck mixers, the following mixing procedure was adopted:

1. Mix aggregate, cement, and 3/4 of water for 3 minutes

2. Stop the mixer for 5 minutes (total time 8 minutes)

3. Mix for 2 minutes (total time 10 minutes)

4. Stop the mixer for 5 minutes (total time 15 minutes)

5. Mix for 2 minutes (total time 17 minutes)

6. Stop the mixer for 5 minutes (total time 22 minutes)

7. Mix for 2 minutes (total time 24 minutes)

8. Stop the mixer for 5 minutes (total time 29 minutes)

9. Add the remaining mixing water

10. Mix for 2 minutes (total time 31 minutes)

11. Measure the slump (seeking 4 inches, adjust if necessary) and measure air content.

12. Cast the specimens, consolidating by vibration

Curing of Test Specimens

Most of the test specimens were cured in 100% R.H.(fog) for 14 days prior to being placed in one of the two controlled temperature and humidity environments (25% R.H. or 50% R.H. at 73°F). This period of 14 days was found to be typical for job-curing in the Los Angeles area. For comparison purposes, a few specimens were fog-cured for 28 days prior to being transferred to drying environments.

Length Change and Strain Measurements

All measurements of expansion on the test specimens began about six hours after casting, immediately after removal from the molds. The specimens were then placed in 100% R.H. and measurements were made daily

for 1 week, then weekly for about 3 months, and monthly after about 90 days. Length changes in the Rubin bars were measured in the comparator and strains in the prisms were measured with a mechanical strain gage.

Theoretical Consideration

As unreinforced and unstressed concrete dries, it shrinks (compresses) and no damge results from the shrinkage. However, if the shrinkage is resisted or restrained by reinforcement, tensile stresses can be induced of sufficient magnitude to cause the concrete to crack. These cracks, referred to as shrinkage cracks, are not only unsightly but often allow ingress of water and other particles which can cause more severe damage. If the concrete portion of reinforced concrete can be placed in compression prior to drying, the tensile stresses resulting from shrinkage must first overcome the compressive stresses already present before the concrete itself will undergo a tensile state which could result in cracking.

Shrinkage-compensating concrete expands during the curing period, and if this expansion is properly restrained (resisted), the steel reinforcing is stretched, placing the concrete to which it is bonded in compression. An ideal expansion-shrinkage curve is shown in Figure 6. The expansion during the curing period (origin to point A) is resisted by reinforcing and the concrete is being compressed. As the concrete enters the drying period A to B, i.e., is placed in service, the concrete begins to shrink. This shrinkage is actually, in terms of strain, tensile in direction, but this tension must first overcome the "built-in" compression before the concrete undergoes a tensile stress i.e., the strain curve as shown in Figure 6 from A to B must drop below the "zero" line to enter the tensile stress zone where the concrete might crack. For the conditions shown in Figure 6, the concrete, after shrinkage, is still in compression; therefore the concrete will not crack due to shrinkage stresses. The problem in designing a structure of shrinkage-compensating concrete then, is to provide the required restrained expansion to overcome the shrinkage the structure is expected to undergo. The amount of shrinkage to be expected in a given structure is principally dependent upon the localized environment of the structure. Obtaining the required restrained expansion is dependent upon the interplay between shrinkage-compensating cement content, the percentage of reinforcing steel, and the size of the member. It should be emphasized that the concrete begins to "shrink" immediately after removal from fog curing, but the important aspect is whether or not and to what extent the shrinkage drops below the zero line into the zone of negative strain.

Test Results

Compressive Strengths. Results of compressive strength tests on unrestrained cylinders 3 inches in diameter and 6 inches long are presented in Figure 7 as a function of cement content and in Figure 8 as a function of water-cement ratio. In both Figure 7 and Figure 8 the straight lines only show trends and do not represent approximate least square lines. It can be seen in Figure 7 that there are no significant differences.

for a given cement content, in the strength of shrinkage-compensating and portland cement concrete with or without air. As indicated in Figure 8, however, the strengths of the shrinkage-compensating concretes tend to be a little higher at water-cement ratios below about 0.50. Perhaps the most significant fact is that although the shrinkage-compensating concrete expands while curing and therefore should theoretically have a lower strength, the test results indicate that it is at least as strong as ordinary portland cement concrete. As expected, both air-entrained concretes (shrinkage-compensating and portland cement) show lower strengths than those without air. Table 2 shows compressive strengths of restrained 1 inch by 5 inch prisms (p=0.30%) after 14 and 28 days of fog curing.

Young's Moduli. Figure 9 shows Young's moduli of shrinkage-compensating concrete as a function of cement content. The curve represents the trend for unrestrained concrete (3- x 6-inch cylinders) while the one point represented by the square is the average value for five 1-inch by 5-inch mesh-reinforced prisms. The moduli of the restrained prisms averaged 3.61 x 10^6 pounds per square inch which represents an increase of 12 percent over the unrestrained value (3.22) at the same cement content (705 pounds per cubic yard). The difference is attributable principally to the fact that the expansion of the prisms was limited by the mesh, resulting in a "tighter" concrete and thus one having a higher modulus. Table 2 shows Young's moduli for restrained 1-inch by 5-inch prisms (p=0.30%) after 14 and 28 days of fog curing. Although the compressive strengths showed sizeable increases for the 28-day values, the Young's moduli increased very little over the 14-day value. Reasons for this may include the effects of the expansion occurring between 14 and 28 days upon the stiffness, of which Young's modulus is a measure.

Expansion and Shrinkage - Rubin Bars. Expansion and shrinkage of Rubins made with 7.5SC and with p=0.19% (3/16-inch bar) are presented in Figure 10. Shrinkage in 25% RH was ultimately about 12% higher than in 50% RH. Comparing these curves with the ideal curve shown in Figure 6, either insufficient expansion took place during curing or there was insufficient restraint to prevent the curves from dropping below the "zero" line. It should be mentioned that had the Rubins been shrinking in a higher humidity, such as 75% RH, the shrinkage curve might have been closer to the zero line.

Similar curves for 7.5SCA are presented in Figure 11. Shrinkage in 25% RH was ultimately about 14% higher than in 50% RH. A comparison of 7.5SC and 7.5SCA curves is shown in Figure 12 for Rubins shrinking in 50% RH. The 14-day expansions were almost equal for 7.5SC and 7.5SCA. At 147 days shrinkage of the 7.5SCA Rubins was about 6% higher than the 7.5SC Rubins. Considering the durability advantages of the air-entrained concrete, the slight increase in shrinkage may be inconsequential.

The effects of different amounts of restraint are shown in Figure 13 for 7.5SC Rubins in 50% RH. There seems to be a delicate relationship between amount of restraint -- in this case the diameter of a threaded

rod -- and the expansion and subsequent shrinkage. One would expect, since it is the steel that provides the restraint which in turn induces the compression into the concrete, that the more steel the better. As the steel percentage increases, the amount of initial expansion decreases, and the amount of precompression in the concrete increases. An optimum amount of reinforcing probably exists for each combination of concrete mix, configuration of structure, and subsequent dyring environment. Figure 13 indicates, as far as the data have progressed, that the three curves may approach each other in time, in which case the p=0.19% would seem to be the most economical since it requires the least steel. As expected, shrinkage for p=0.19% was 14% higher than for p=0.36% and 25% higher than for p=0.58%.

The effects of the cement content upon expansion and shrinkage of Rubin bars with p=0.19% are shown in Figure 14. As stated earlier, the amount of expansion during the curing period increases as the amount of shrinkage-compensating cement increases, other things being equal. Figure 14 verifies this statement and the subsequent shrinkage results reflect the effects of the higher expansions. The curve for 11.0 SC more closely resembles the ideal curve of Figure 6 than any of the others, but the shrinkage did drop below the zero line slightly. Concrete, of course, does have a limited tensile strength, so perhaps the slight amount of tensile shrinkage strain shown could be tolerated without cracking the concrete. As indicated in Figure 14, the shrinkage strains were related to the cement content i.e., highest in 11.0 SC and lowest in 7.5 SC.

<u>Expansion and Shrinkage - Prisms</u>. Expansion and shrinkage of 1-inch by 5-inch prisms of 7.5SC with p-0.30% are shown in Figure 15. At 175 days shrinkage in 25% RH was about 25% higher than in 50% RH. Comparing Figure 15 with Figure 10 it is interesting to note that ultimate negative strains in 25% RH were not much different, but there were some basic differences in the specimens and reinforcement which enter the picture. The Rubins (3 inches square) were reinforced with a threaded rod at p=0.19%, while the prisms (1-inch by 5-inch) were reinforced with 2-inch by 2-inch no. 14 mesh (see Table 1). It should also be recalled that the 1-inch by 12-inch edges of the prisms were sealed to prevent loss of moisture, to simulate a continuous thin shell 1 inch thick; drying was permitted only from the 5-inch by 12-inch faces. Since the Rubin bars are proposed as tentative standards, drying was permitted from all four sides. It has been well established previously that higher shrinkage can be expected from smaller (and thinner) specimens.[19,20] The most significant factor in comparing Figure 10 and Figure 15 is the difference in reinforcement (0.19% versus 0.30%) and the as yet unclear effects of the configuration of the reinforcement (rod versus mesh). The 14-day expansion of the Rubins was slightly higher than that in the prisms (587 versus 563 microstrain).

Expansion and shrinkage curves for 1-inch by 5-inch prisms of 7.5SCA are presented in Figure 16. The relationships between curves for 25% RH and 50% RH were quite similar to those already presented. At 134 days, shrinkage in 25% RH was about 16% higher than in 50% RH.

Comparison curves for 7.5SC and 7.5SCA in 50% RH are shown in Figure 17, which shows about the same relationship between the two curves as seen in Figure 12 for Rubins. In Figure 17, however, the 14-day expansion of the 7.5SCA is shown to be about 20 percent higher than the 7.5SC (+676 over +563 microstrain). Having entrained air bubbles, and therefore lower strength, the hardening 7.5SCA offered lower resistance to the expansive forces during the curing period. In spite of the higher initial expansion, however, the shrinkage curve for 7.5SCA dropped below that for 7.5SC, and the inherently weaker air-entrained concrete shrank 22% more in the same period than did the 7.5SC. Regardless of the analysis, however, shrinkage of the 7.5SCA at 133 days was only about 21% higher than for the 7.5SC. As stated earlier in regard to Figure 12, this disadvantage may be partially offset by the advantage of greater durability in the 7.5SCA.

Expansion and shrinkage curves for 2-inch by 5-inch prisms of 7.5SC with p=0.30% are shown in Figure 18. At 119 days, shrinkage in 25% RH was about 30% higher than in 50% RH. This difference between the two curves is slightly greater than the corresponding differences between 1-inch by 5-inch prisms (25%) from Figure 15. Continued research may reveal the reasons for these differences.

Expansion and shrinkage curves for 4-inch by 5-inch prisms of 7.5SC with p=0.30% are presented in Figure 19. Shrinkage in 25% RH at 119 days was about 14% higher than in 50% RH. The rather significant factors concerning the curves of Figure 19 are the close resemblance to the ideal curve of Figure 6. Although the curve for 25% RH did drop slightly below the zero line, it appears that the 50% RH line may approach zero asymptotically or, at most, drop below very slightly in time. These curves in Figure 19 emphasize the size or mass effects of the larger 4-inch thick prisms compared with the smaller ones. The quantitative effects are only now beginning to come to light, but continued research should point the way to rational design of thin-shell structures reinforced with mesh rather than with typical reinforcing bars. The mesh does provide a certain restraint in a second direction; that is, a direction perpendicular to but in the same plane as the longitudinal reinforcement.

Effects of size (thickness) of prism are shown in Figure 20 for 7.5SC concrete, p=0.30%, and shrinkage in 50% RH. Ultimately, there was very little difference in the shrinkage of 1-inch and 2-inch prisms, but a dramatic difference between them and the 4-inch prisms. It is further interesting to note that the 14-day expansion of the 4-inch prisms exceeded that of the others by about 12%.

The effects of the amount of restraint on the expansion and shrinkage of 1-inch by 5-inch prisms of 7.5SC are shown in Figure 21, with shrinkage being in 50% RH. As indicated in Figure 13 for Rubins, the higher the percentage of reinforcement, the lower the initial expansion. Subsequent shrinkage values in 50% RH showed questionable value of reinforcement higher than 0.30% (Figure 21) and inject the question as to what the performance would be in a 1-inch prism reinforced with mesh at a value somewhere between p=0% and p=0.30%. This possibility will be investigated

in FY73. As expected, the curve for p=0% shows the highest expansion, and the shrinkage curve stayed above the zero line, but it should be emphasized that expansion of this concrete was not resisted and therefore the concrete was in a state of tension from the beginning. In addition, the strength properties of this concrete are relatively low due to the large expansions. Tests at p=0% are usually conducted to evaluate the expansion potential of a given cement.

A summary of the effects of different amounts of restraint on the 14-day expansions of 1-inch by 5-inch prisms is presented in Figure 22. It should be reemphasized, however, that there appears to be an optimum amount of a given type of restraint for each concrete mix, interdependent upon the drying environment the concrete is expected to undergo and upon the configuration of the member.

Examples of the possible benefits of expansive concretes are indicated in Figure 23 and in Figure 24. Figure 23 shows expansion and shrinkage curves for 1-inch by 5-inch prisms of 7.5SC and 7.5PC, with both subjected to drying in 25% RH. The reduction in ultimate negative strain, and therefore in tensile stress, in the 7.5SC concrete is quite dramatic. In addition, after 91 days shrinkage in 7.5SC was about 8% less than in 7.5PC. Similar results are shown in Figure 24 for prisms shrinking in 50% RH. After 91 days, shrinkage was about 20% less in 7.5SC than in 7.5PC.

Creep Tests. Results of tests in which 2-inch prisms were loaded in 50% RH at $0.25f'_c$ (25% of their ultimate strength) and at $0.50f'_c$ are shown in Figure 25. For comparison purposes, corresponding curves are also shown for tests made in connection with thin-shell roofs reported in Reference 20 (NCEL TR-704). Although the cement content of the portland cement mix (8.25 sacks) was slightly higher than that of the shrinkage-compensating mix (7.5 sacks), this slight difference cannot account for the rather large differences in negative creep-plus-shrinkage strains observed between the two mixes. The negative strain at $0.25f'_c$ was 43% lower for the expansive concrete than the portland cement concrete; the corresponding reduction at $0.50f'_c$ was 30%. The prism size, type and percentage of reinforcement, fog curing time (14 days), and shrinkage environment were identical for both types of concrete. At 147 days, creep-plus-shrinkage of the shrinkage-compensating concrete was about 13% less for $0.25f'_c$ and 8% less for $0.50f'_c$.

Since little work has been published on the efficacy of welded wire fabric for providing restraint to the expansion of shrinkage-compensating concrete, a rather comprehensive study was undertaken with one concrete mix (7.5SC), three prisms sizes (1-inch, 2-inch, and 4-inch), several percentages of reinforcement, and two drying environments (25% RH and 50%RH). The

results reported herein establish the relationships necessary to enable knowledgeable continuation of the research. The principal items required for rational design of thin-shell (and other) structures of shrinkage-compensating concrete include (1) a realistic estimate of the amount of shrinkage the structure is expected to undergo, (2) the amount of shrinkage-compensating cement required to provide the expansion necessary to overcome the shrinkage; this consideration would include cost-effective combinations of cement content and percentage of reinforcement, and (3) the size and shape of the structure.

The data on Rubin bars presented herein enable relationships to be established with the work of other investigators using different amounts and brands of cement. Therefore, these data are valuable just as are data on concrete cylinders with which one investigator can relate his particular parameters to those of others and eliminate unnecessary duplication. Since Rubin bars are generally accepted as "standard," these tests also enable observation of the effects of changing only one variable at a time.

The data presented herein on fabric-reinforced prisms are believed to be unique and tend to indicate that the size-effect with shrinkage-compensating concrete is somewhat different from that observed in References 19 and 20 for portland cement concrete. Results with the 4-inch prisms did indicate, however, a definite size-effect compared with the smaller prisms (see Figure 20). The unclear portion of this size-effect is the contribution of the four pieces of mesh reinforcement required in the 4-inch prisms to equal the p=0.30% of the other two prisms (see Table 1). The effect of the lateral restraint (provided by the four pieces of mesh) upon the longitudinal strains is, as yet, unknown.

Data reported herein indicate that a shrinkage-compensating concrete mix containing 7.5 sacks per cubic yard and with p=0.30% does not provide sufficient expansion to prevent the shrinkage curve from dropping below the zero line in 1-inch or 2-inch prisms drying in either 25% RH or in 50% RH (Figure 15 and Figure 18), but comes much closer in the 4-inch prisms. With all the basic data gathered from the 7.5SC mix, a smaller effort will be required to establish optimum cost-effective cement content and reinforcement combinations to meet any design eventuality.

PLANS FOR FY-73

Thin-Shell Roofs and Slabs

1. To obtain results applicable to coral concrete, a limited but conclusive study will be conducted on expansive concrete made with limestone aggregate to determine (a) amount of expansion corresponding to certain cement contents; (b) shrinkage effects in various drying environments; (c) strength and Young's modulus properties.

2. A limited study will be made of a few mixes of lightweight expansive concrete, both sand-lightweight and all-lightweight.

Ferro-Cement

1. An experimental ferro-cement panel will be designed for preparing shrinkage-compensating cement mortar. Expansions and shrinkage measurements will be made on these panels. Specimens will also be cut from the panels for obtaining flexural and compressive strengths and Young's moduli.

Construction of a Thin-Shell Roof

In cooperation with a field activity which may be planning construction of a roof or other type of thin-shell structure, design information will be furnished by NCEL to enable the structure to be made with expansive concrete. Knowledge of the likely shrinkage to be expected in the locality where the structure is to be built will be coupled with knowledge of the cement content and restraint required to offset that shrinkage. The mix, casting, finishing, and curing recommendations will then be made accordingly.

Construction of a Small Ferro-Cement Boat

Tentatively, it is planned to design and build at NCEL a small experimental ferro-cement boat utilizing expansive mortar throughout. This effort may extend into FY-74, as will the final report on the whole study.

Experimentation with Self-Stressing Cements

Since self-stressing cements are not yet commercially available, experimentation will be subject to availability of the cement from certain manufacturers. NCEL has been told that some of the cement will be made available and experiments will be made with this cement to determine (a) effects of the higher level of expansion on the ferro-cement panels and upon the thin-shell prisms; (b) the efficacy of mesh reinforcement in a box-like configuration to present a triaxial restraint to the expanding cement.

Table 1. Reinforcement Percentages Using Welded Wire Fabric

Prism Thickness, in.	Number of Pieces of Fabric	Spacing and Fabric Openings and Wire Gage	Reinforcement Percentage
1	1	2 in. x 2 in. No. 14	0.30[1]
1	1	2 in. x 2 in. No. 12	0.47
1	1	1 in. x 1 in. No. 14	0.50
1	1	1 in. x 1 in. No. 12	0.78
2	2	2 in. x 2 in. No. 14	0.30
2	2	2 in. x 2 in. No. 12	0.44
2	2	1 in. x 1 in. No. 14	0.50
2	2	1 in. x 1 in. No. 12	0.78
4	4	2 in. x 2 in. No. 14	0.30
4	4	2 in. x 2 in. No. 12	0.44
4	4	1 in. x 1 in. No. 14	0.50
4	4	1 in. x 1 in. No. 12	0.78

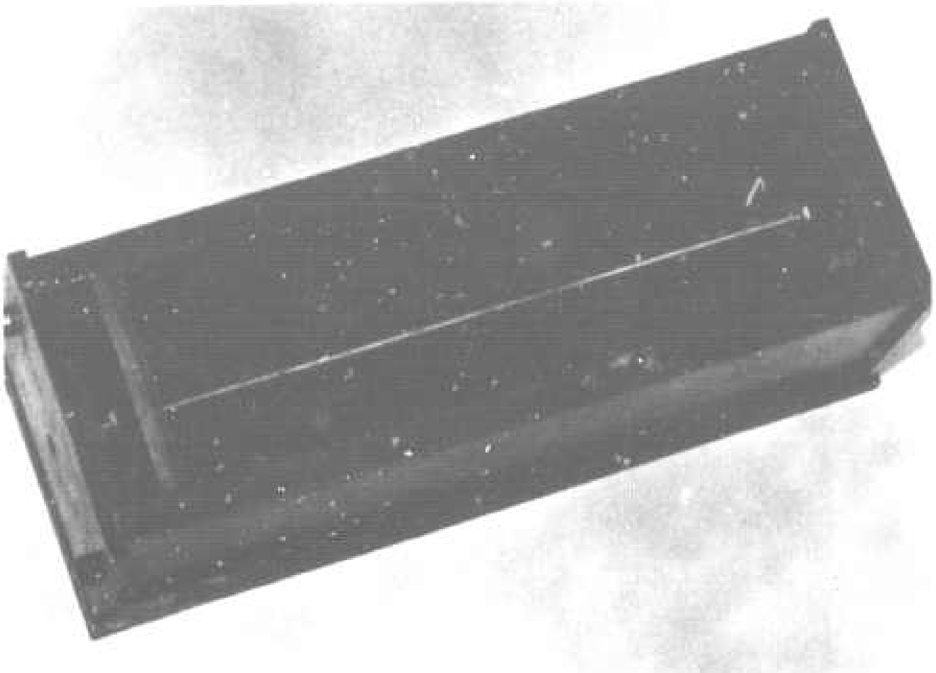
1. Reinforcement percentage = the total cross-sectional area of the horizontal wires at the end of the prism ÷ the total cross-sectional area of the prism, viewed from the end.

Table 2. Strength Properties of Restrained 1 inch by 5 inch prisms, p = 0.30%

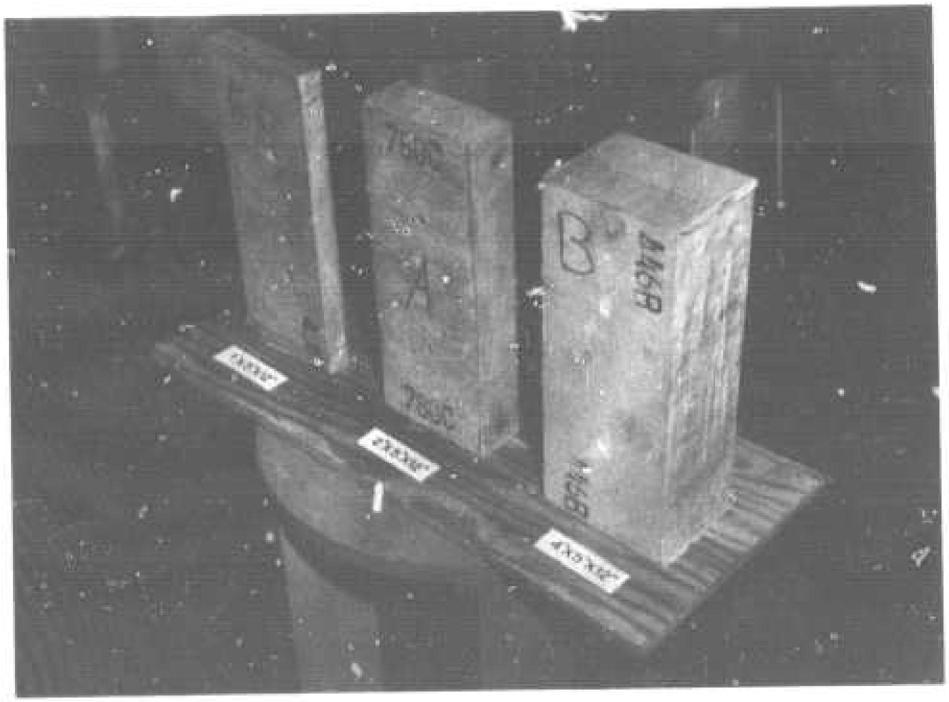
Strength Property	Concrete Mix Designation			
	7.5SC		7.5SCA	
	14 Days[1]	28 Days[2]	14 Days	28 Days
Compressive Strength, psi	5,110	6,020	4,050	4,480
Young's Modulus, 10^6 psi	3.59	3.61	2.90	2.97

1. Tests made after 14 days of curing in 100% RH.

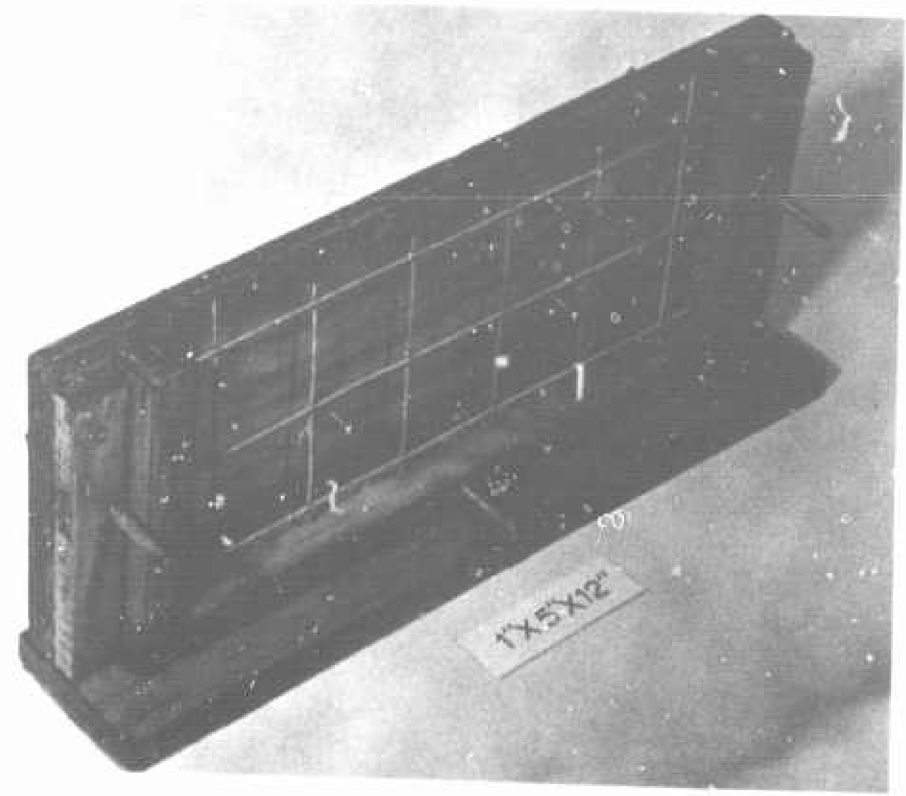
2. Tests made after 28 days of curing in 100% RH.



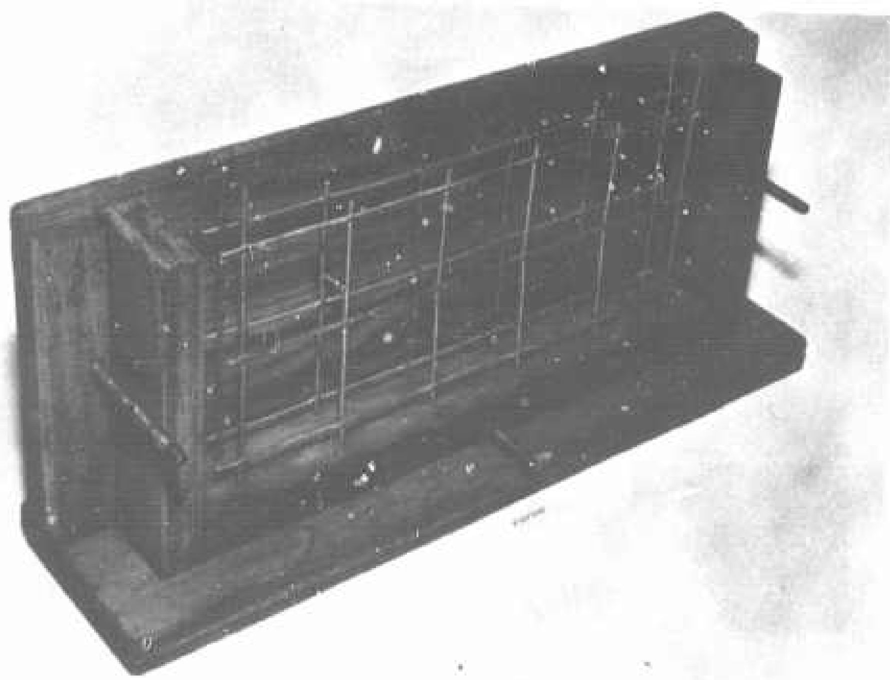
1. Rubin bar molds with threaded bar.



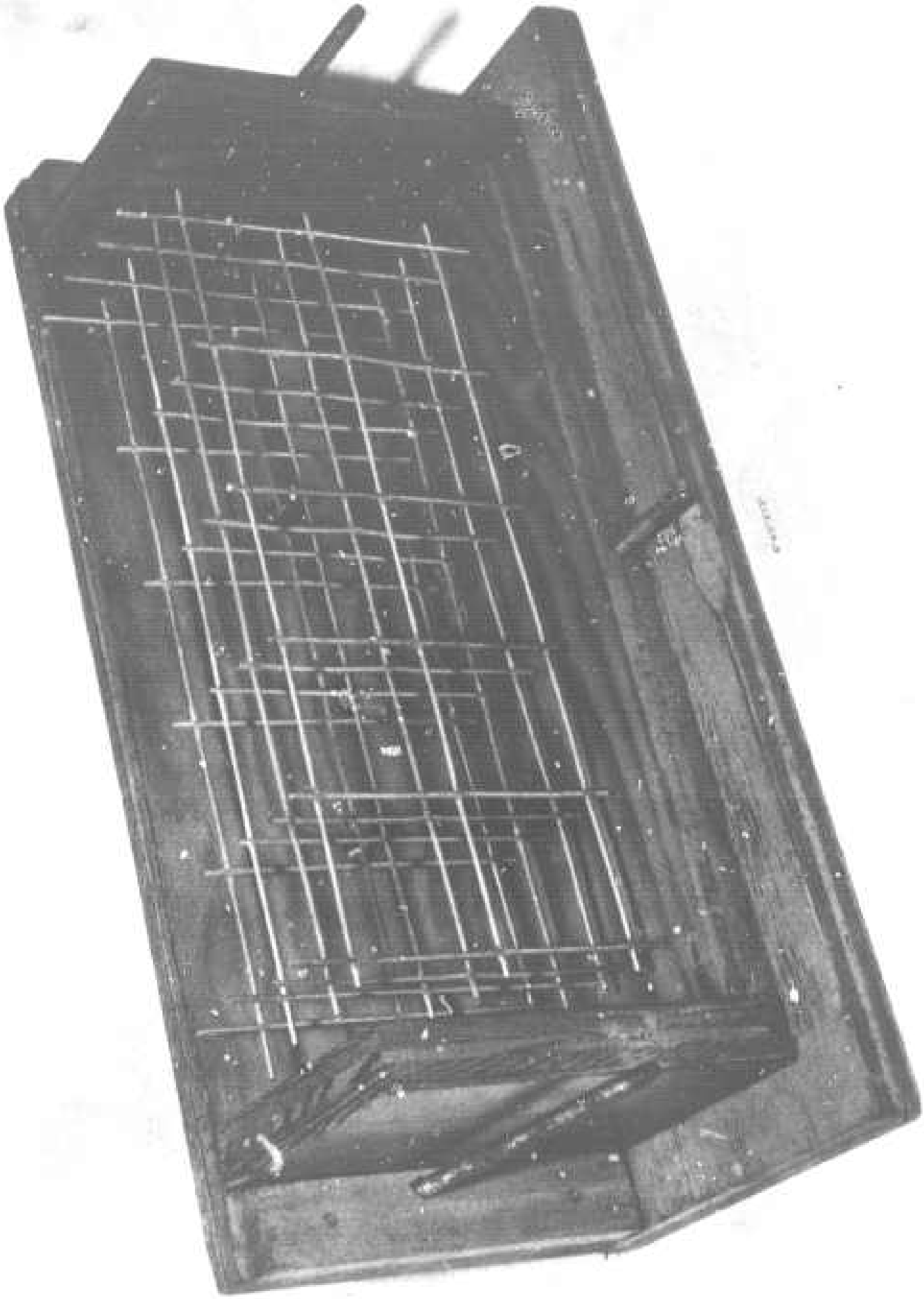
2. Prismatic test specimens.



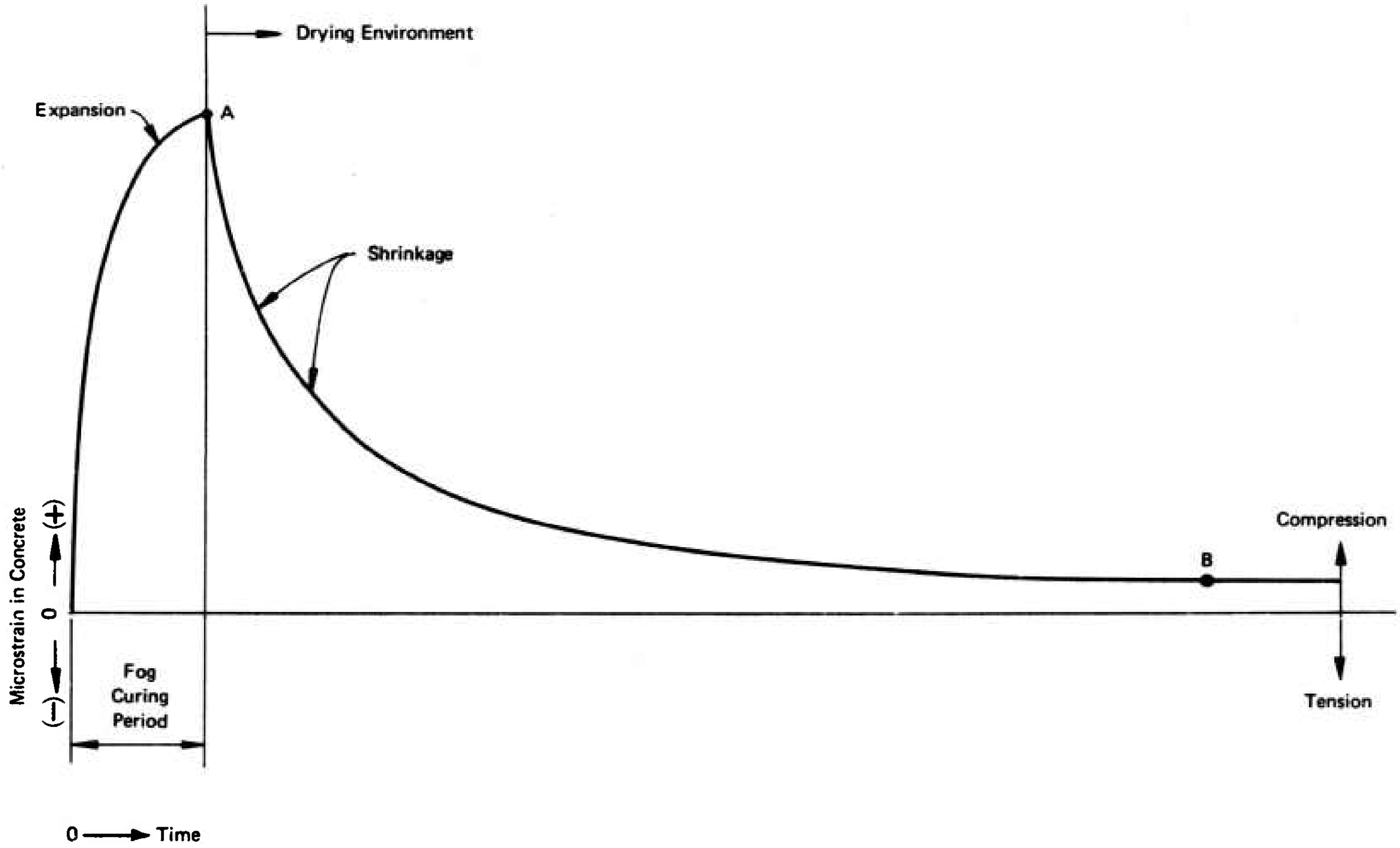
3. Form for prisms 1 inch thick, showing reinforcement.



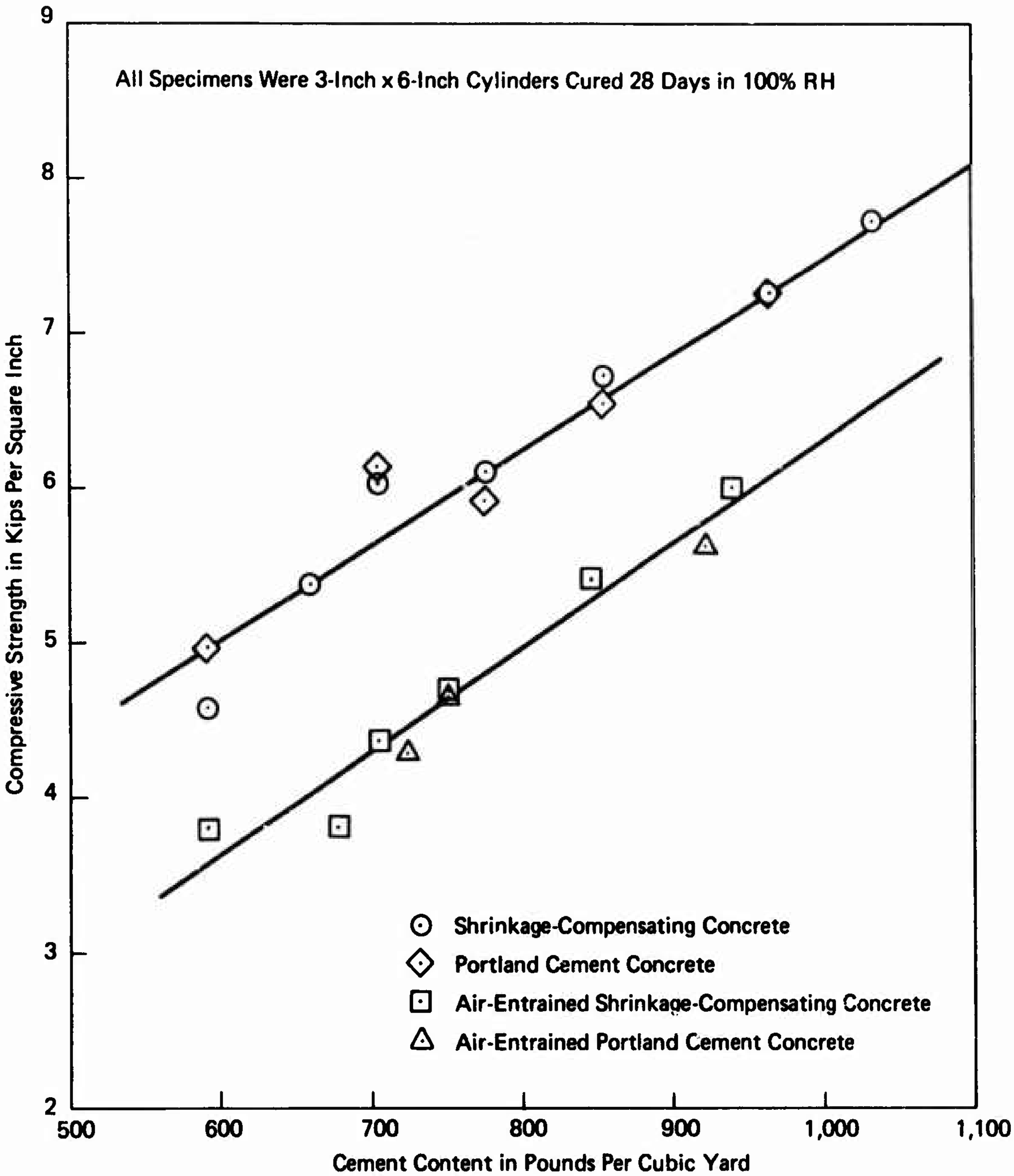
4. Form for prisms 2 inches thick, showing reinforcement.



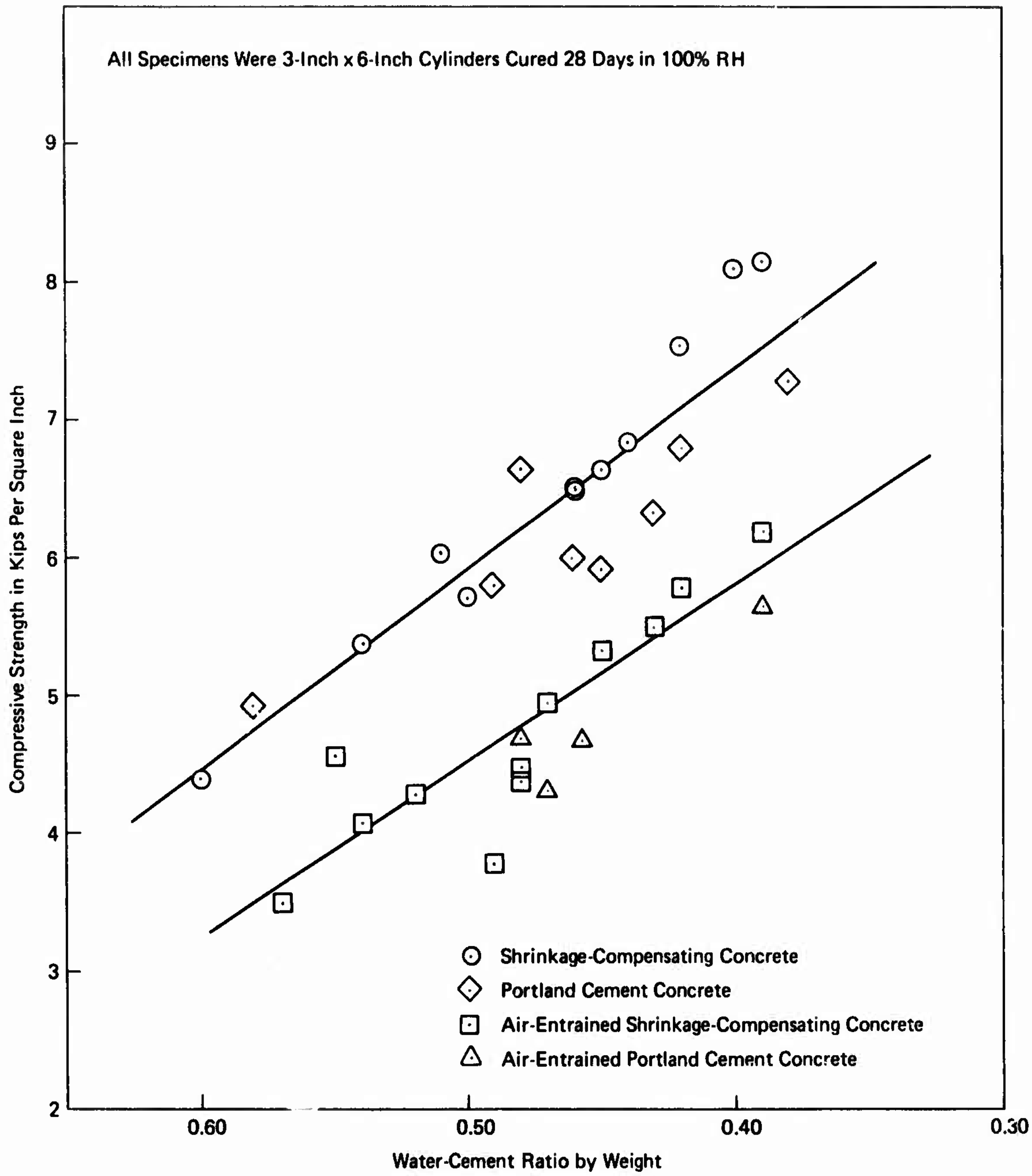
5. Form for prisms 4 inches thick, showing reinforcement.



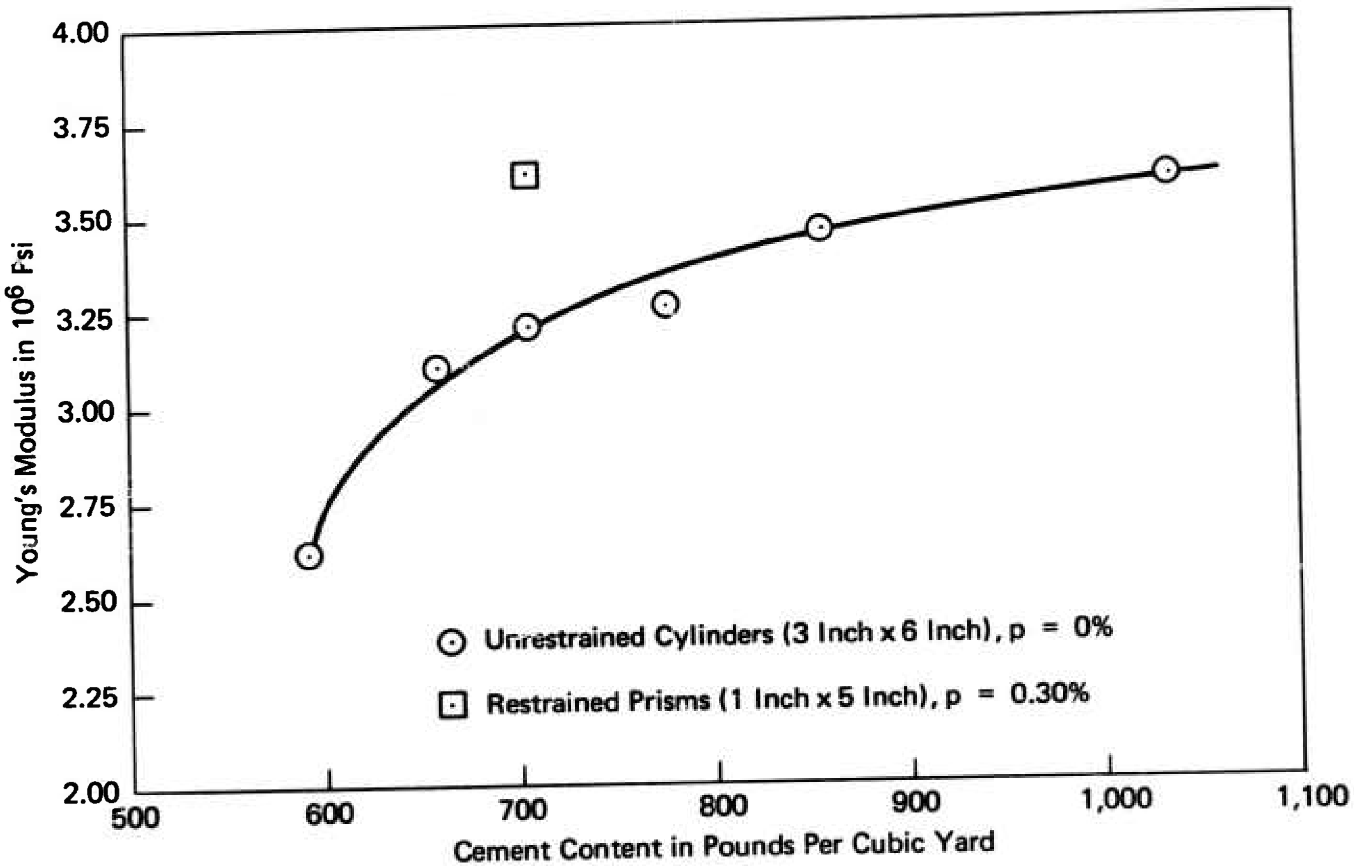
6. Ideal expansion-shrinkage curve for restrained shrinkage-compensating content.



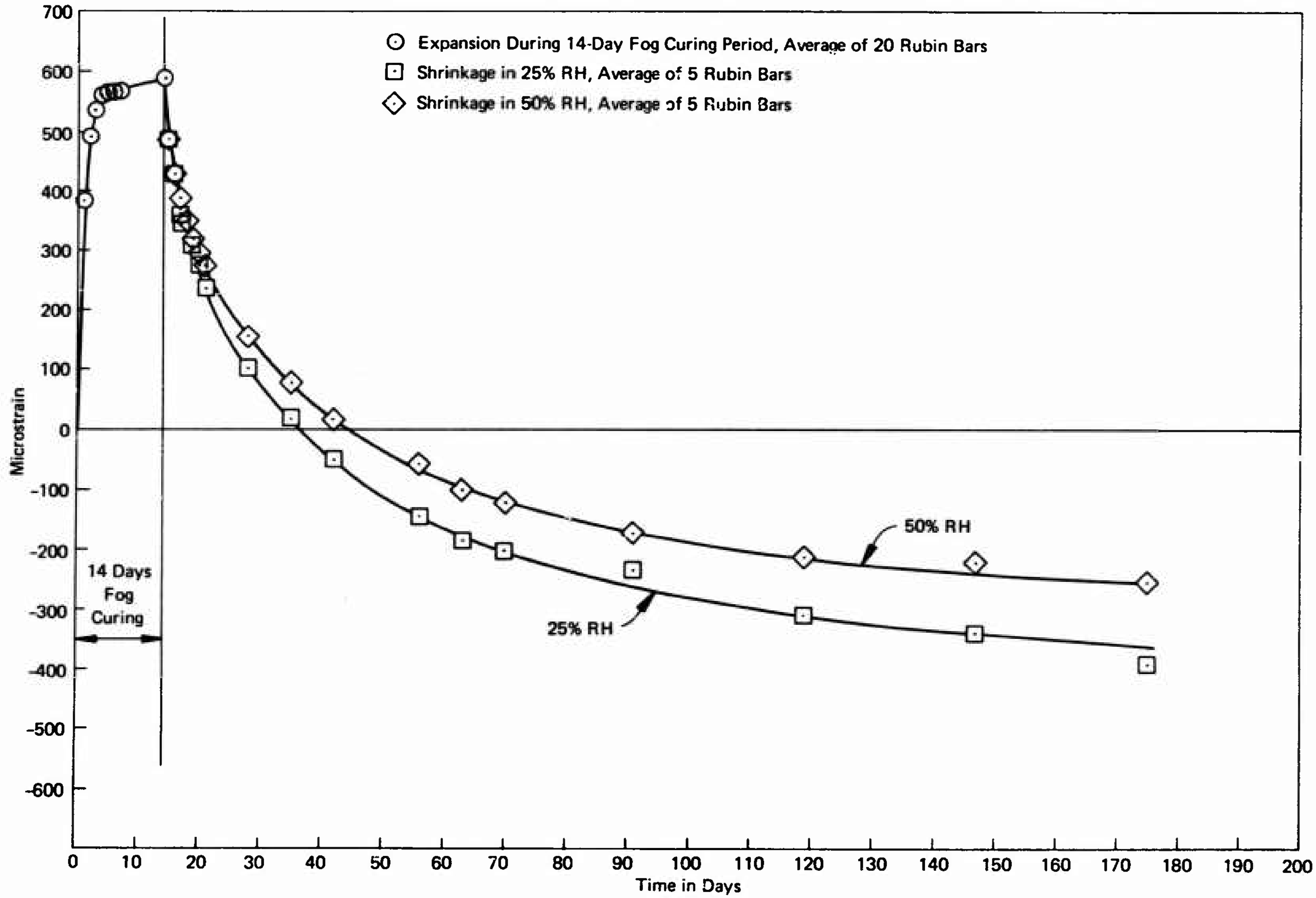
7. Compressive strengths of unrestrained cylinders as a function of cement content.



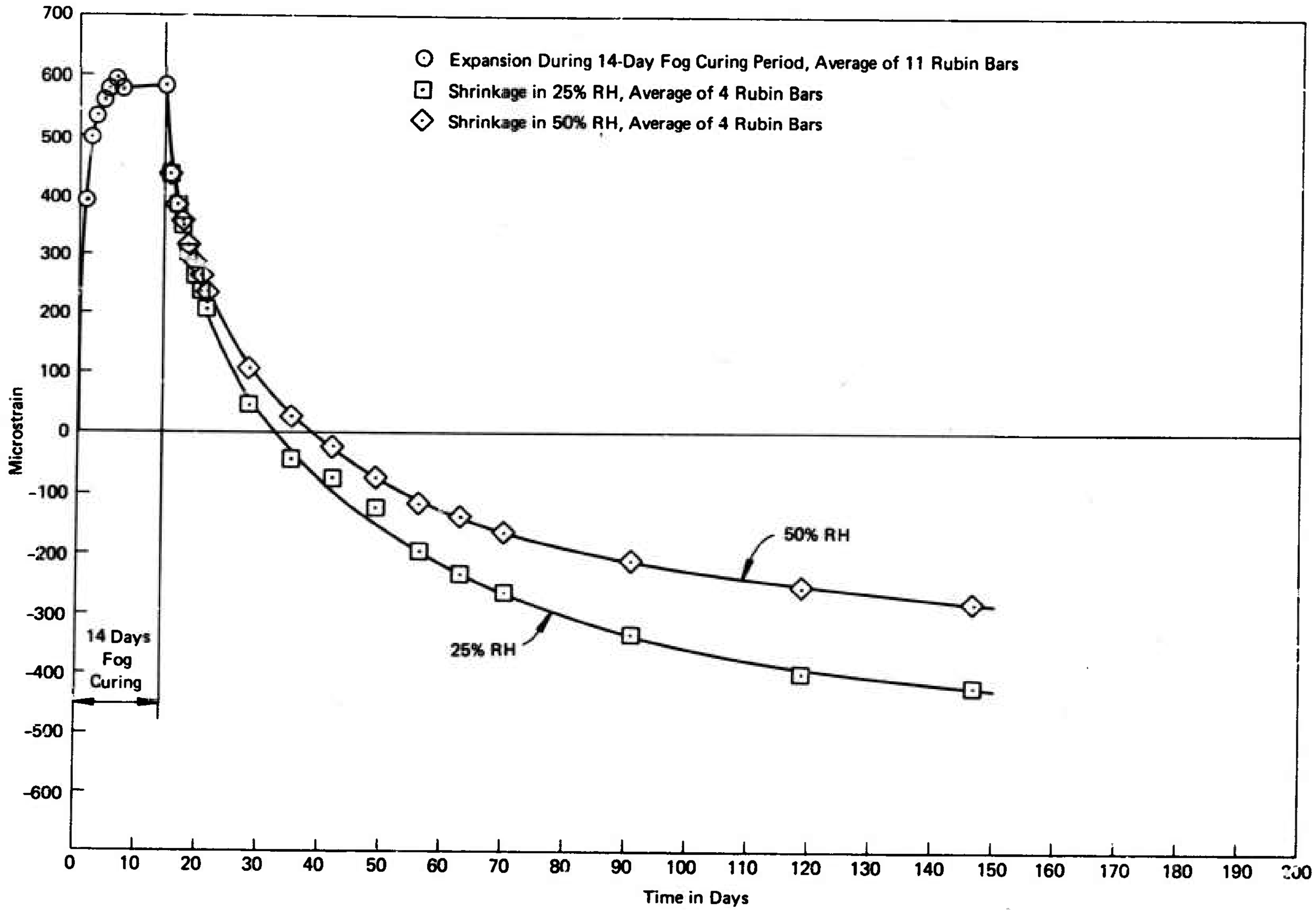
8. Compressive strengths of unrestrained cylinders as a function of water-cement ratio.



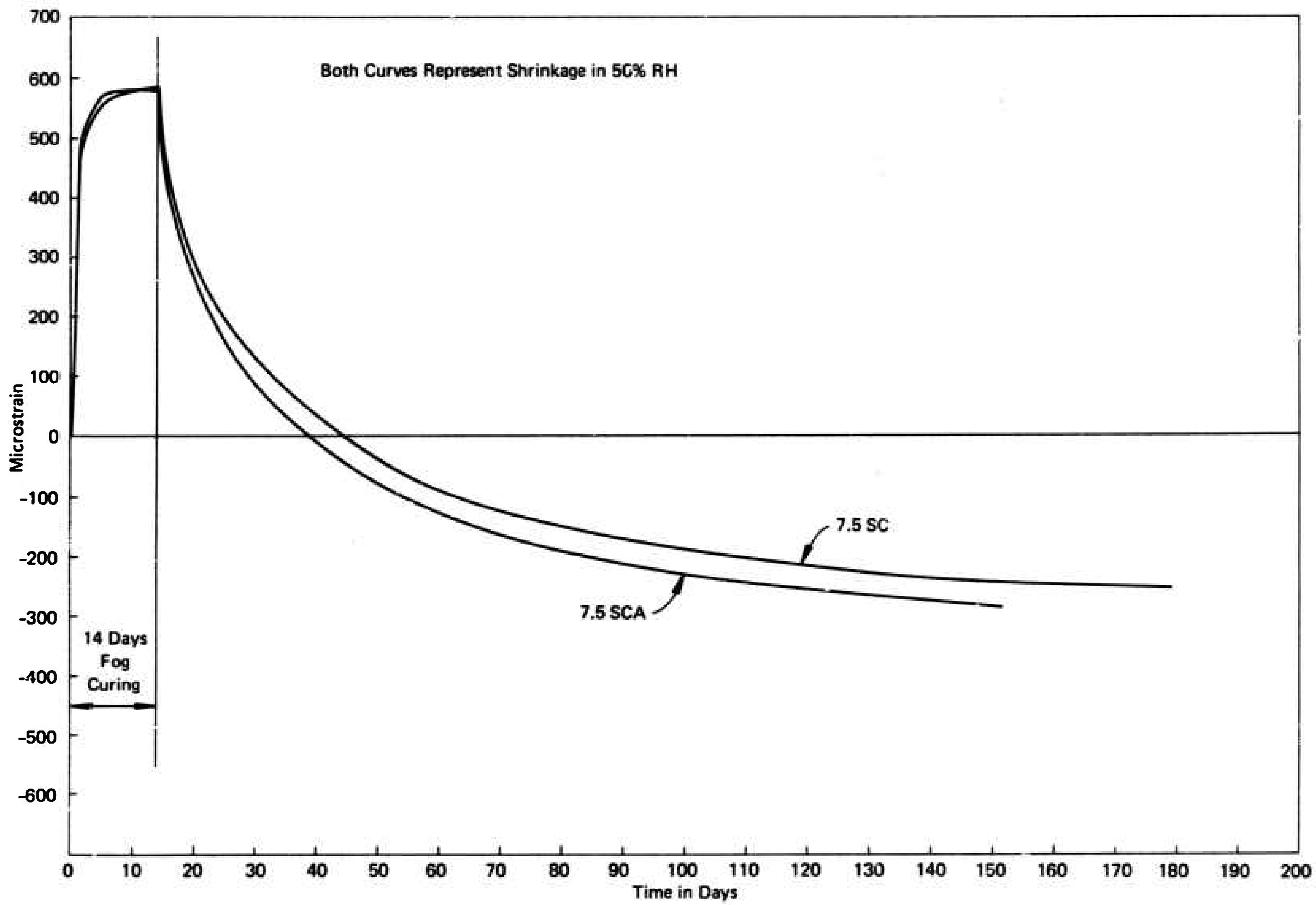
9. Young's moduli of shrinkage-compensating concrete after 28 days of fog curing.



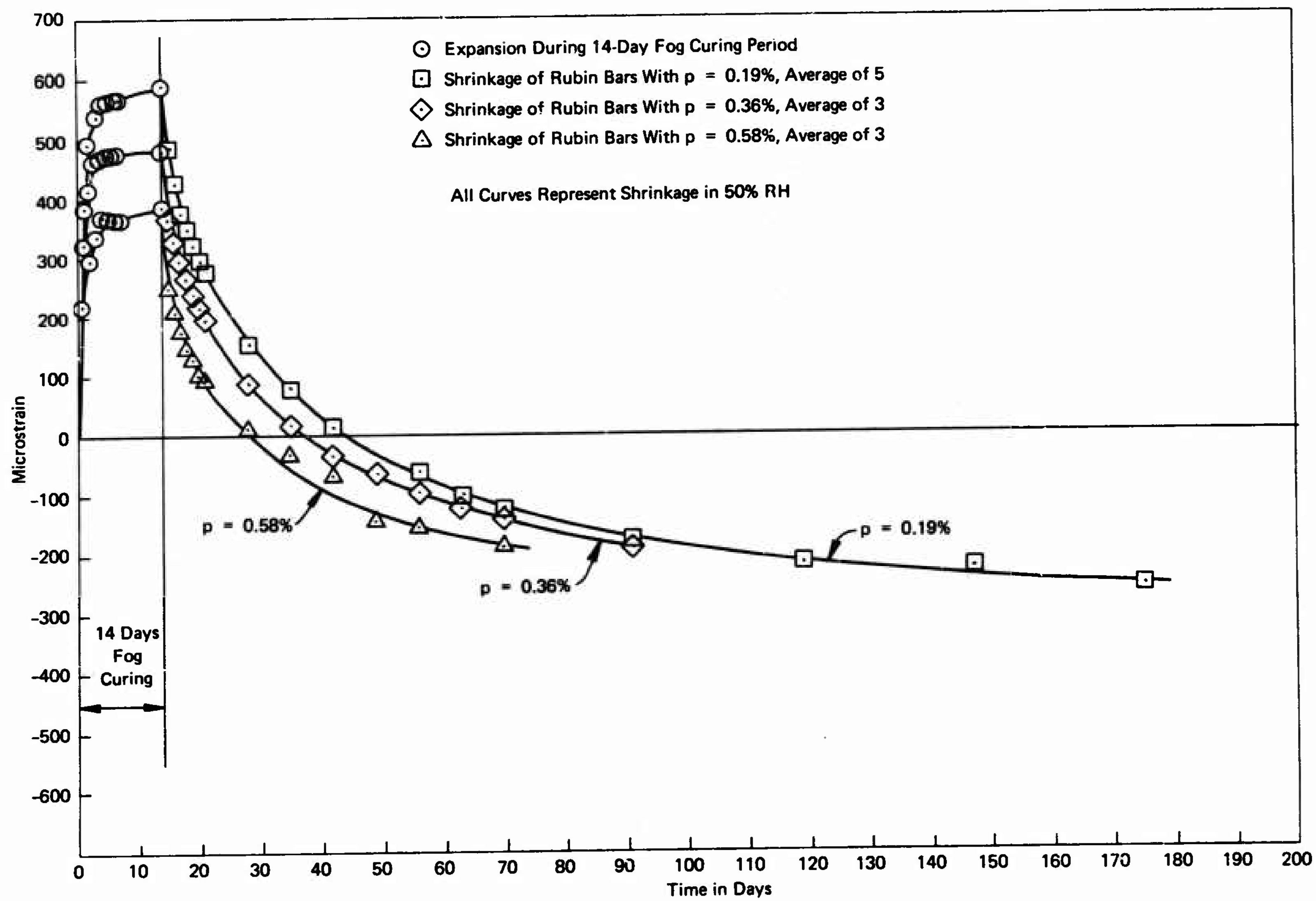
10. Expansion and shrinkage of Rubin bars, p=0.19%, 7.5SC.



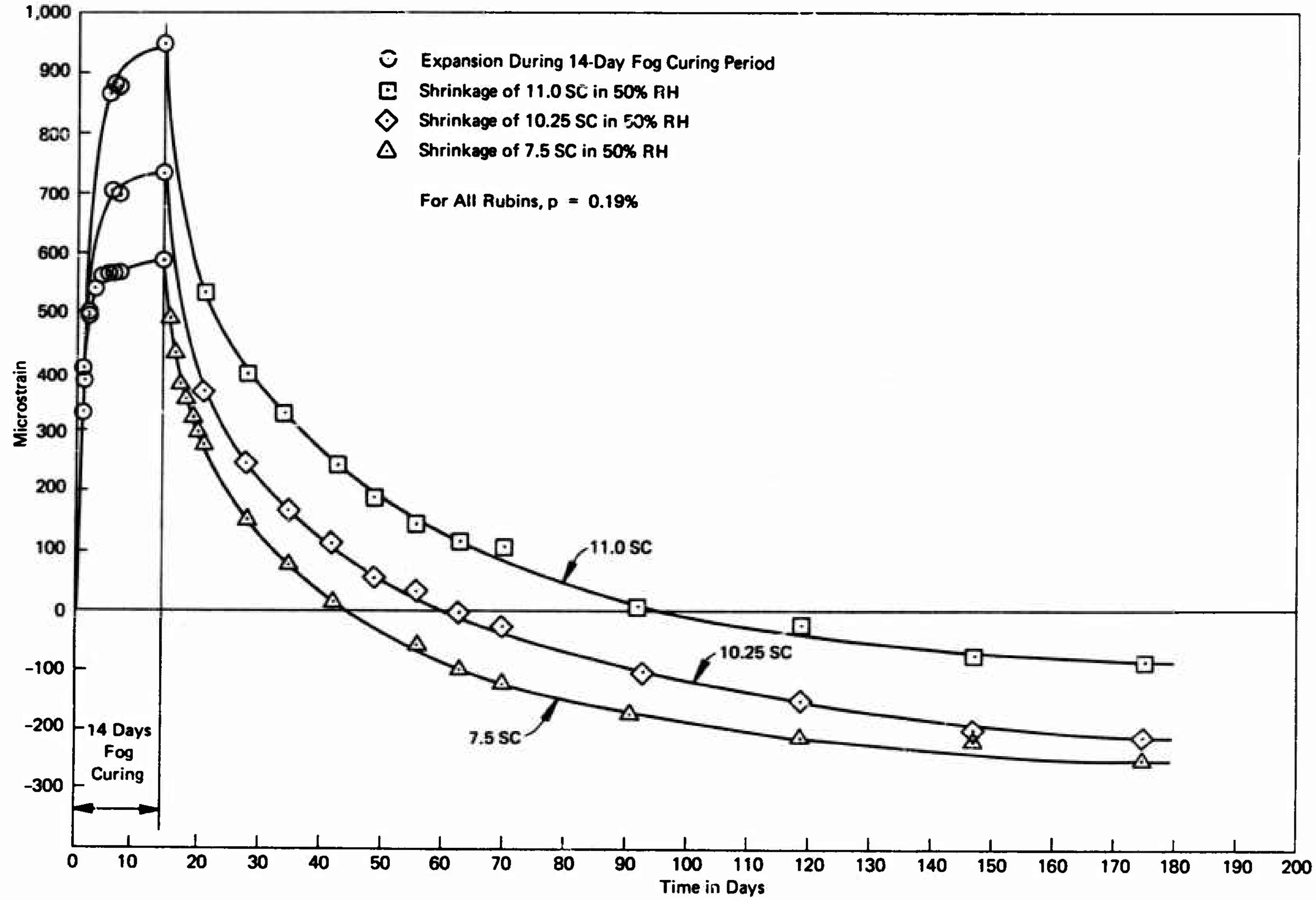
11. Expansion and shrinkage of Rubin bars, p=0.19%, 7.5SCA.



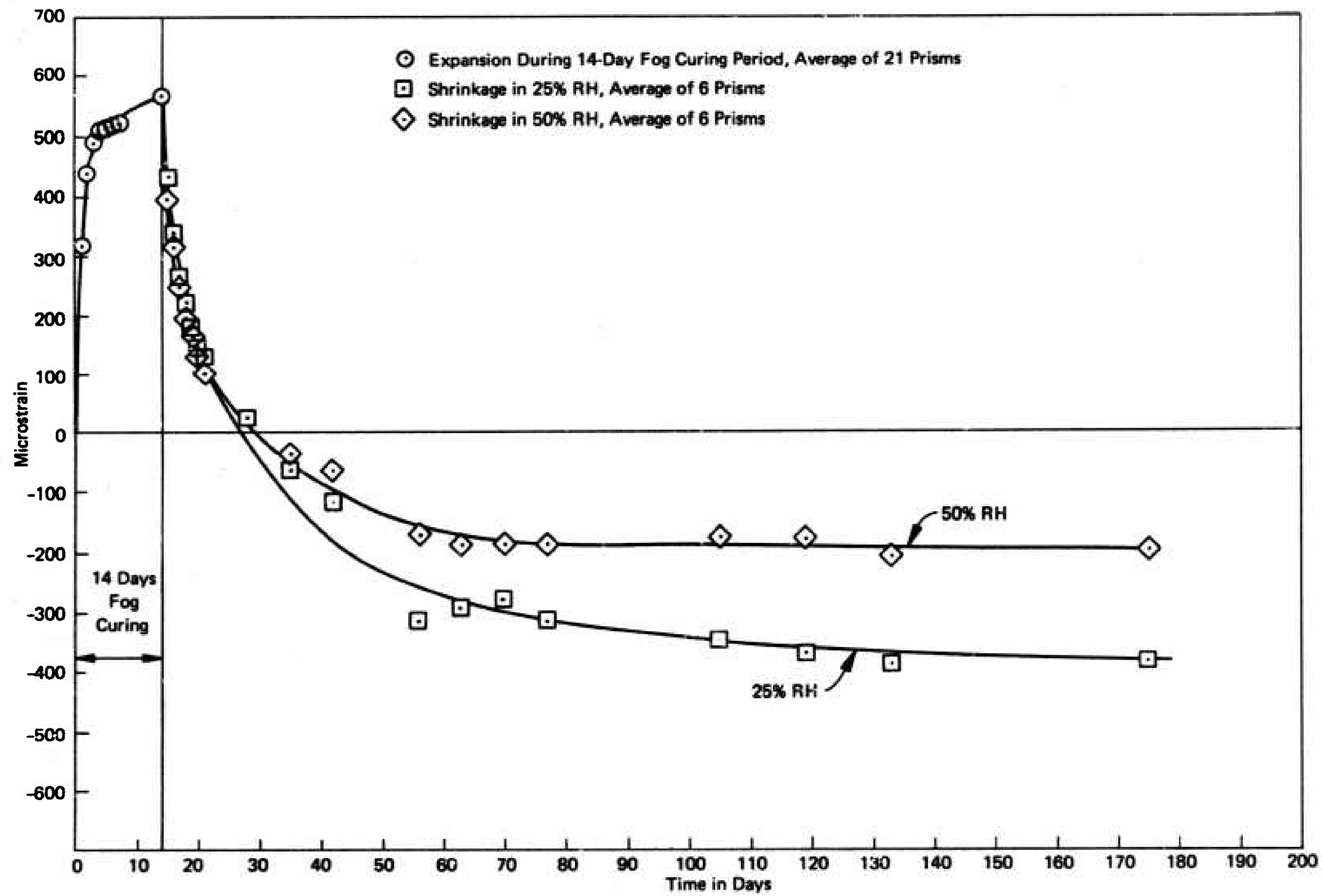
12. Comparison curves for Rubin bars, p=0.19%, 7.5SC and 7.5SCA.



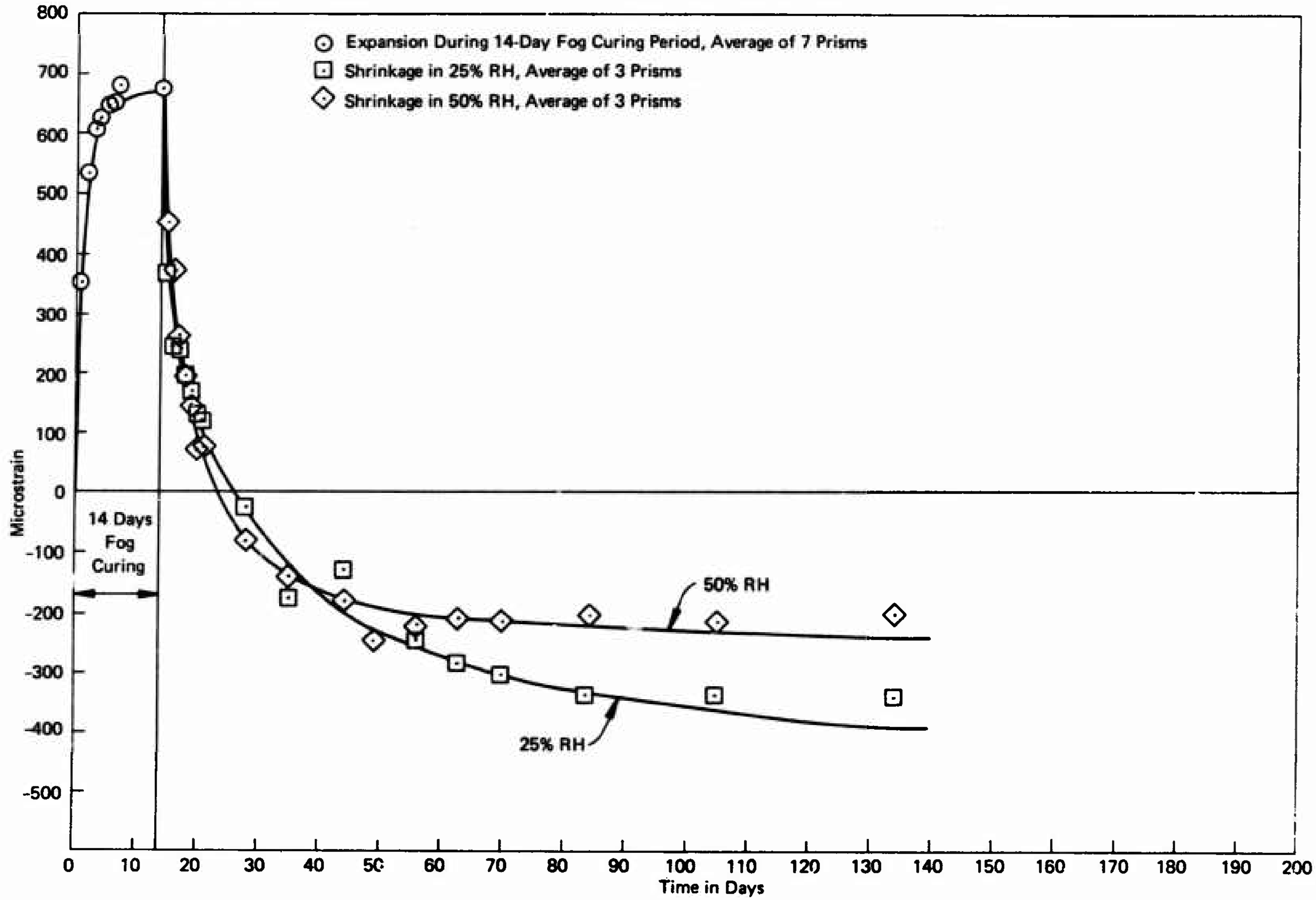
13. Effects of restraint on expansion and shrinkage of Rubin bars, 7.5SC.



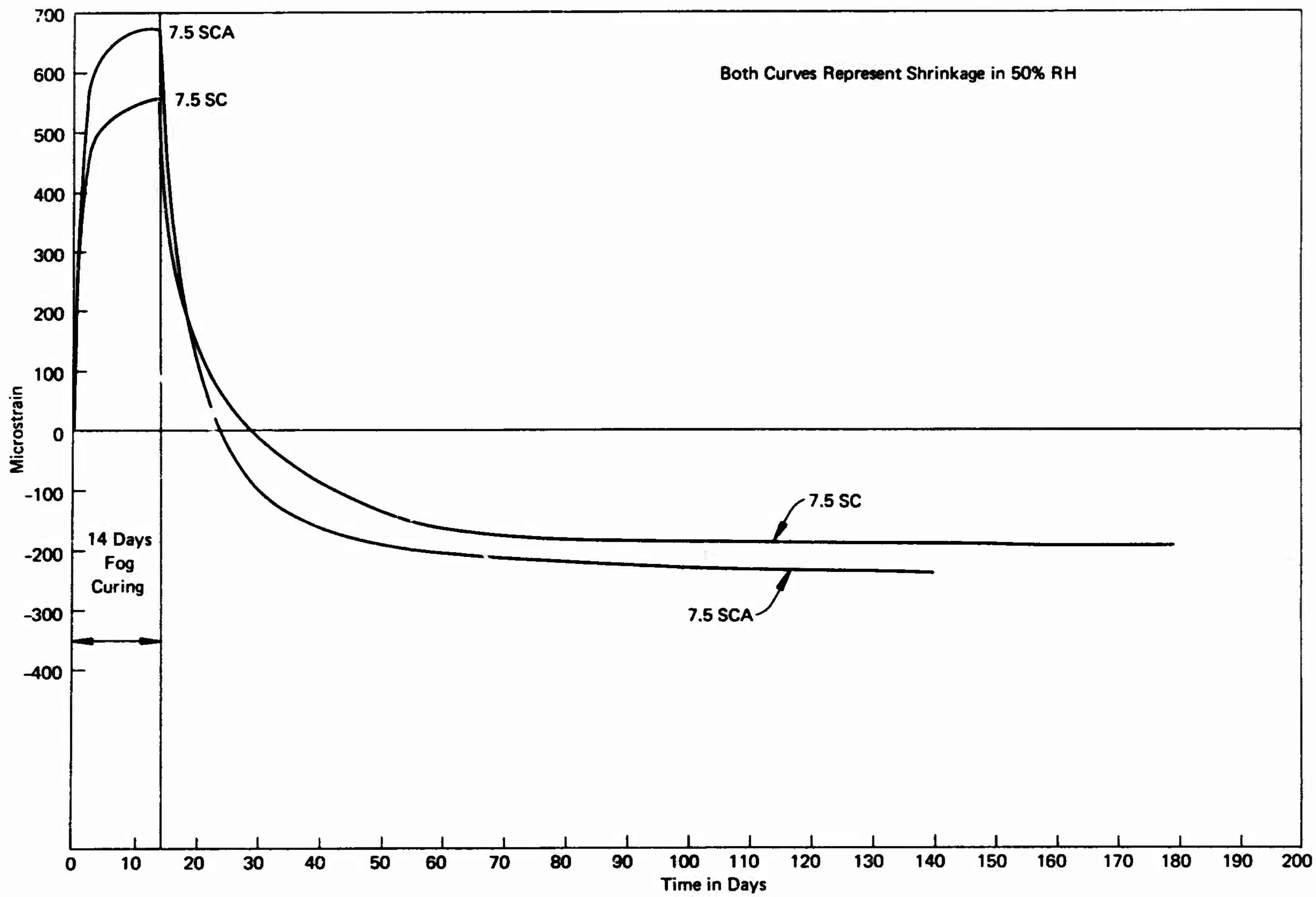
14. Effects of cement content upon expansion and shrinkage of Rubin bars, 7.5SC.



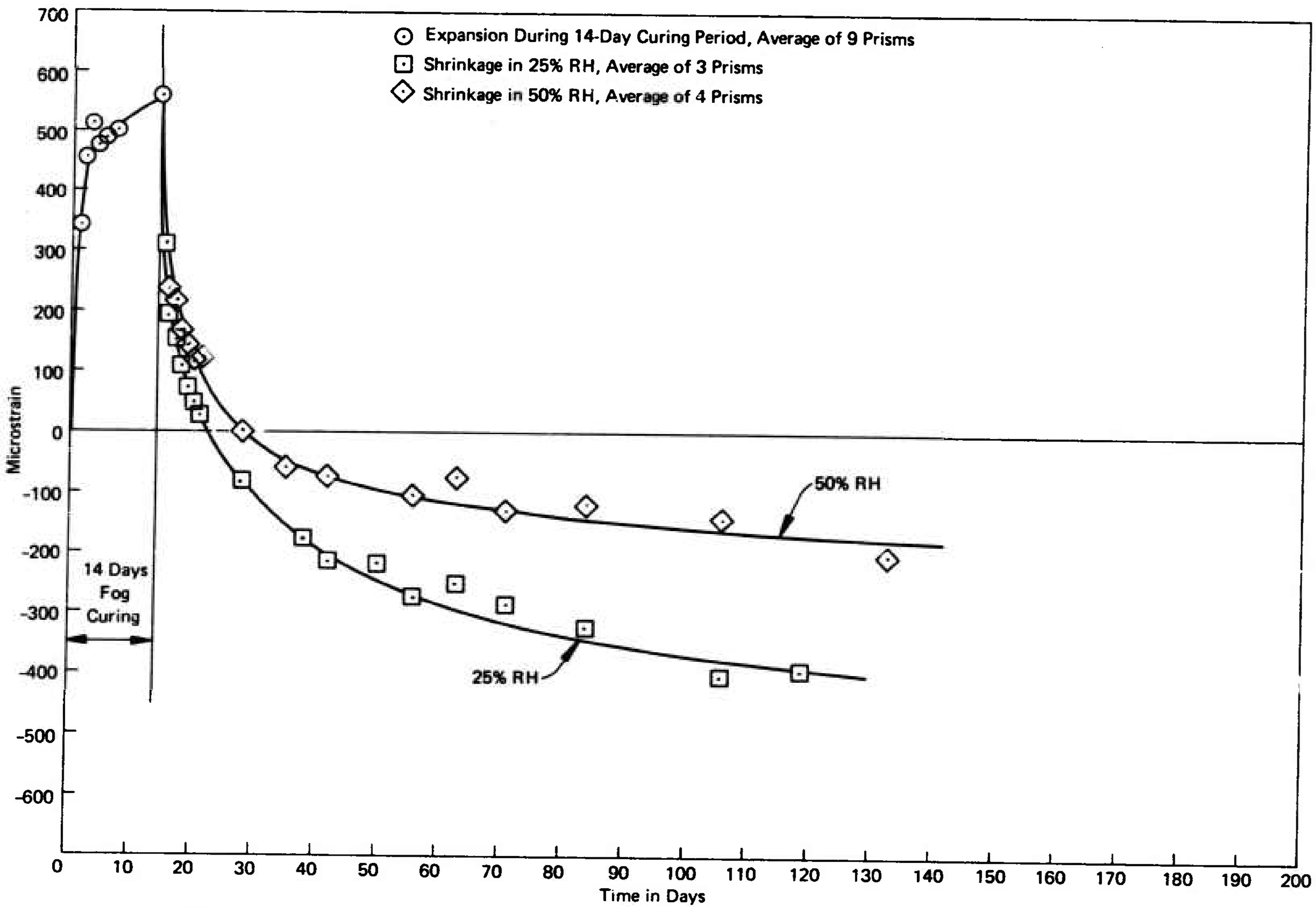
15. Expansion and shrinkage of 1 inch by 5 inch prisms, p=0.30%, 7.5SC.



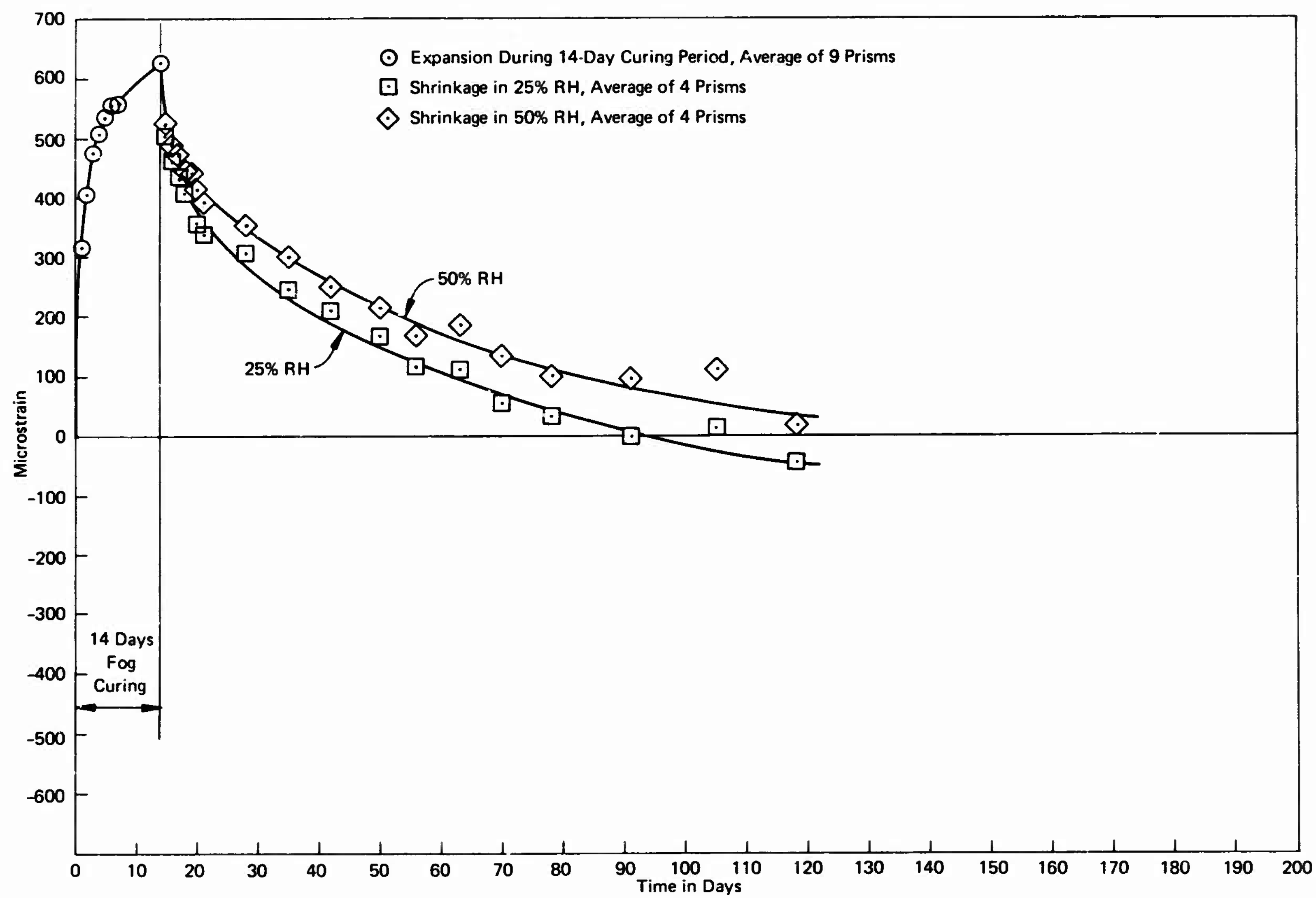
16. Expansion and shrinkage of 1 inch by 5 inch prisms, p=0.30%, 7.5SCA.



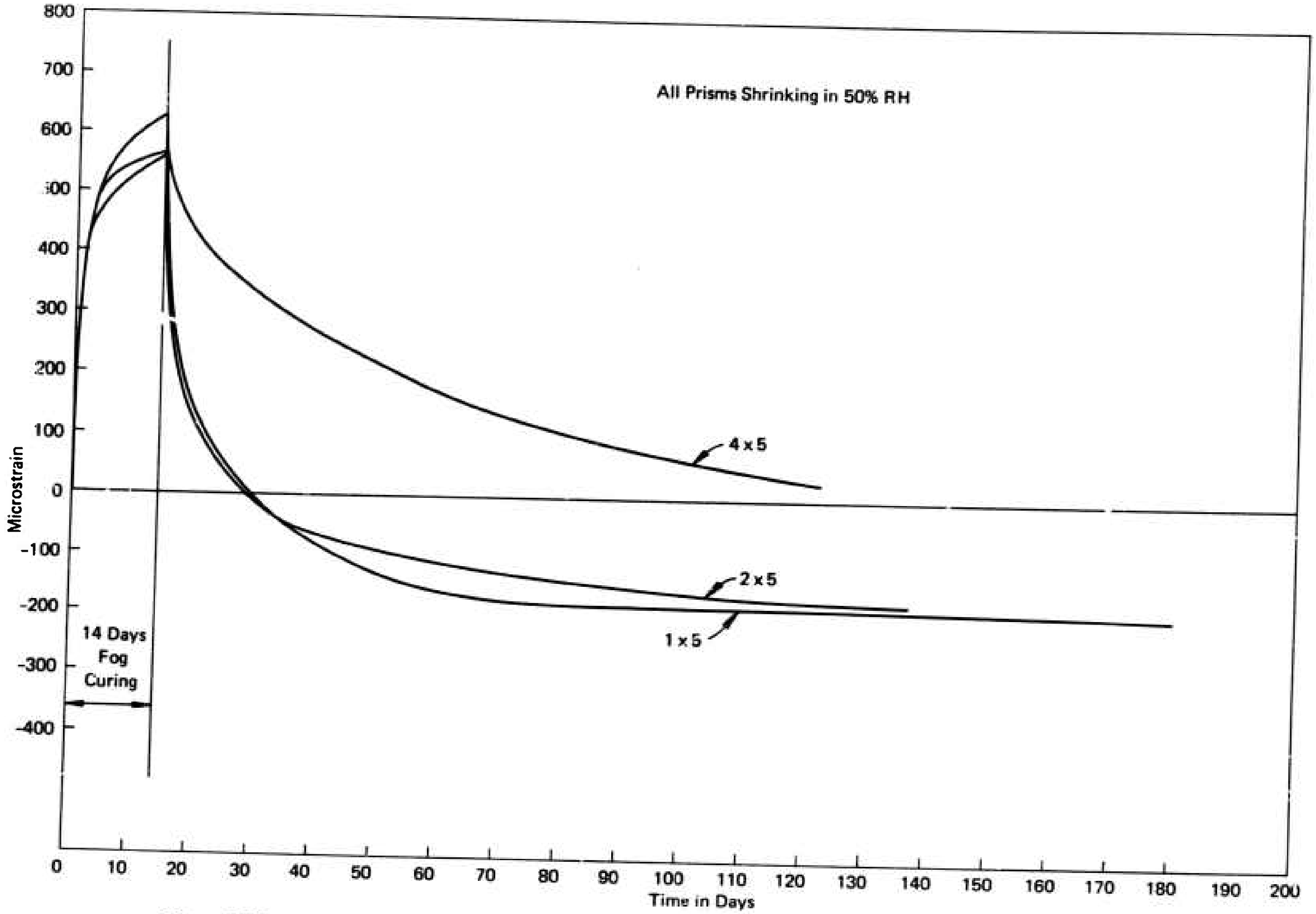
17. Comparison curves for 1 inch by 5 inch prisms, p=0.30%, 7.5SC and 7.5SCA.



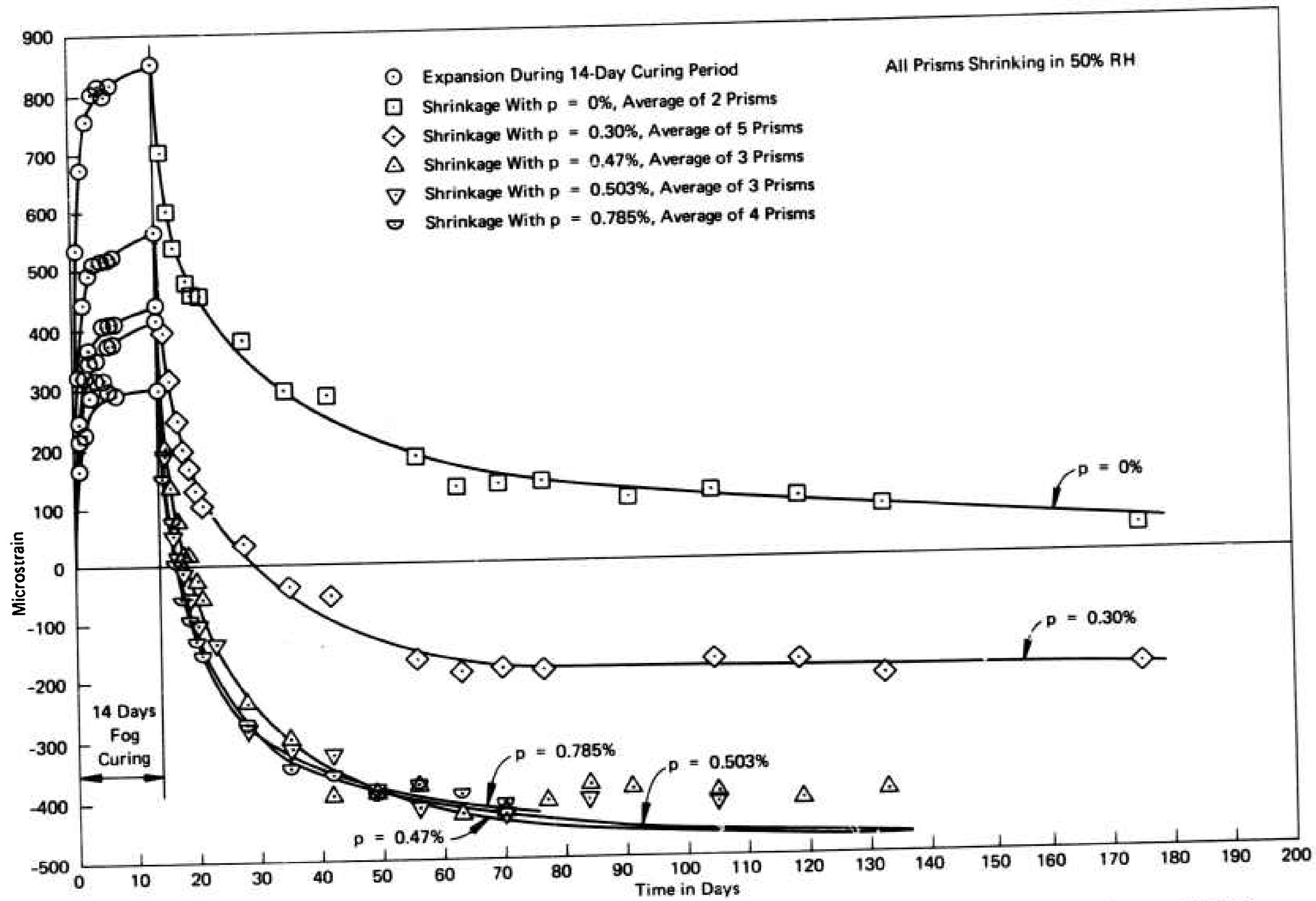
18. Expansion and shrinkage of 2 inch by 5 inch prisms, p=0.30%, 7.5SC.



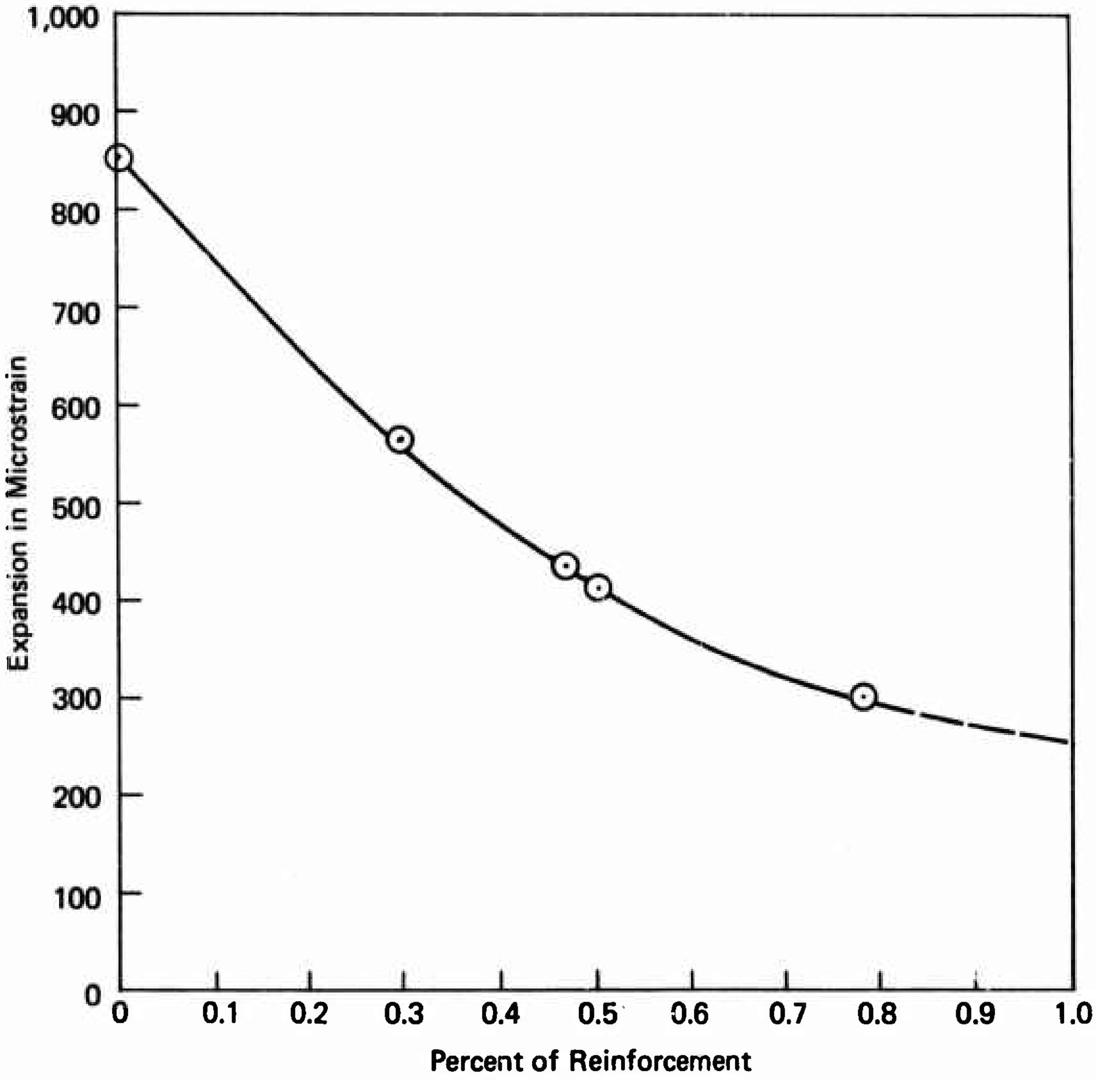
19. Expansion and shrinkage of 4 inch by 5 inch prisms, p=0.30%, 7.5SC.



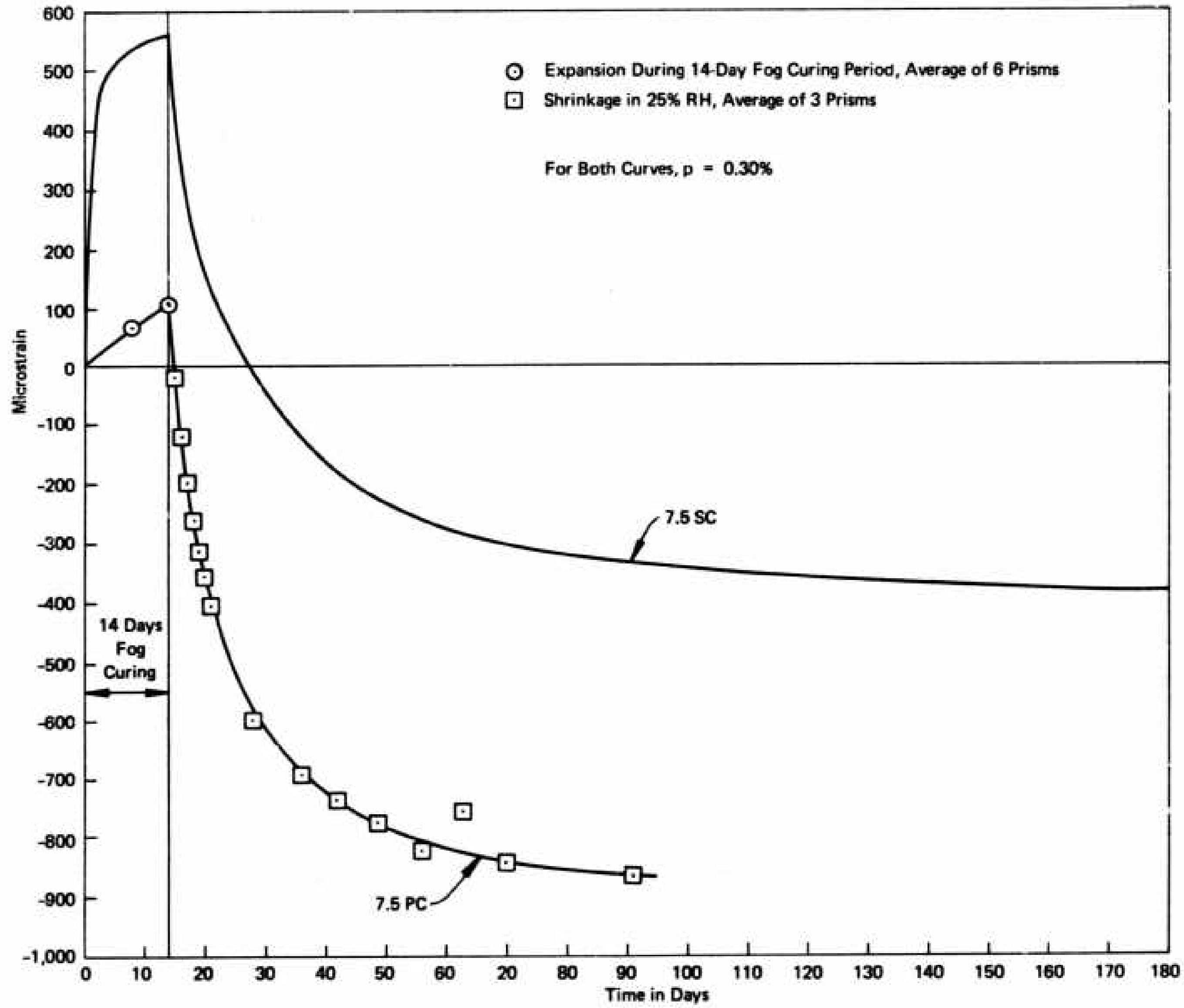
20. Effects of prism size on expansion and shrinkage, p-0.30%, 50% RH, 7.5SC.



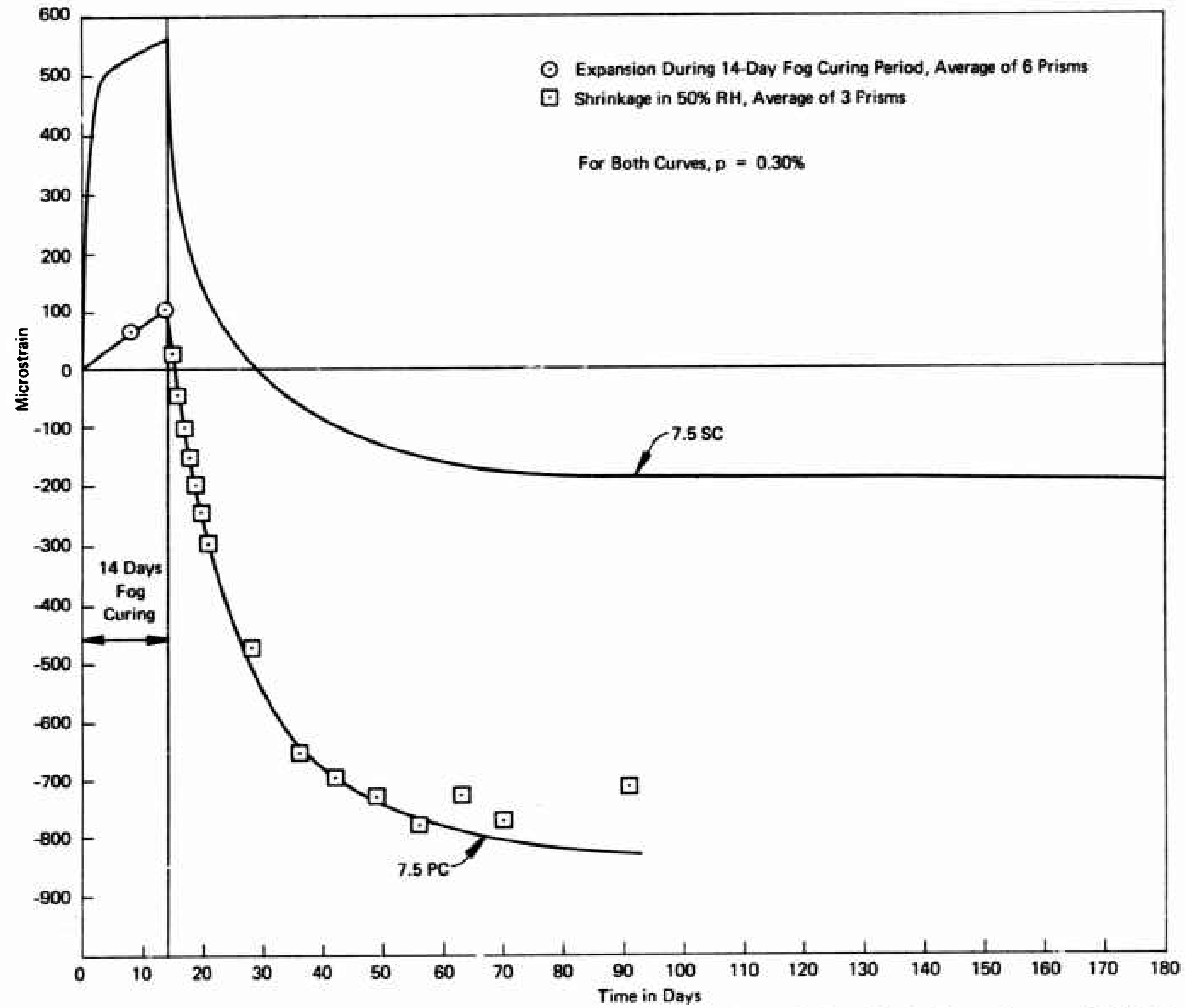
21. Effects of restraint on expansion and shrinkage of 1 inch by 5 inch prisms, 7.5SC.



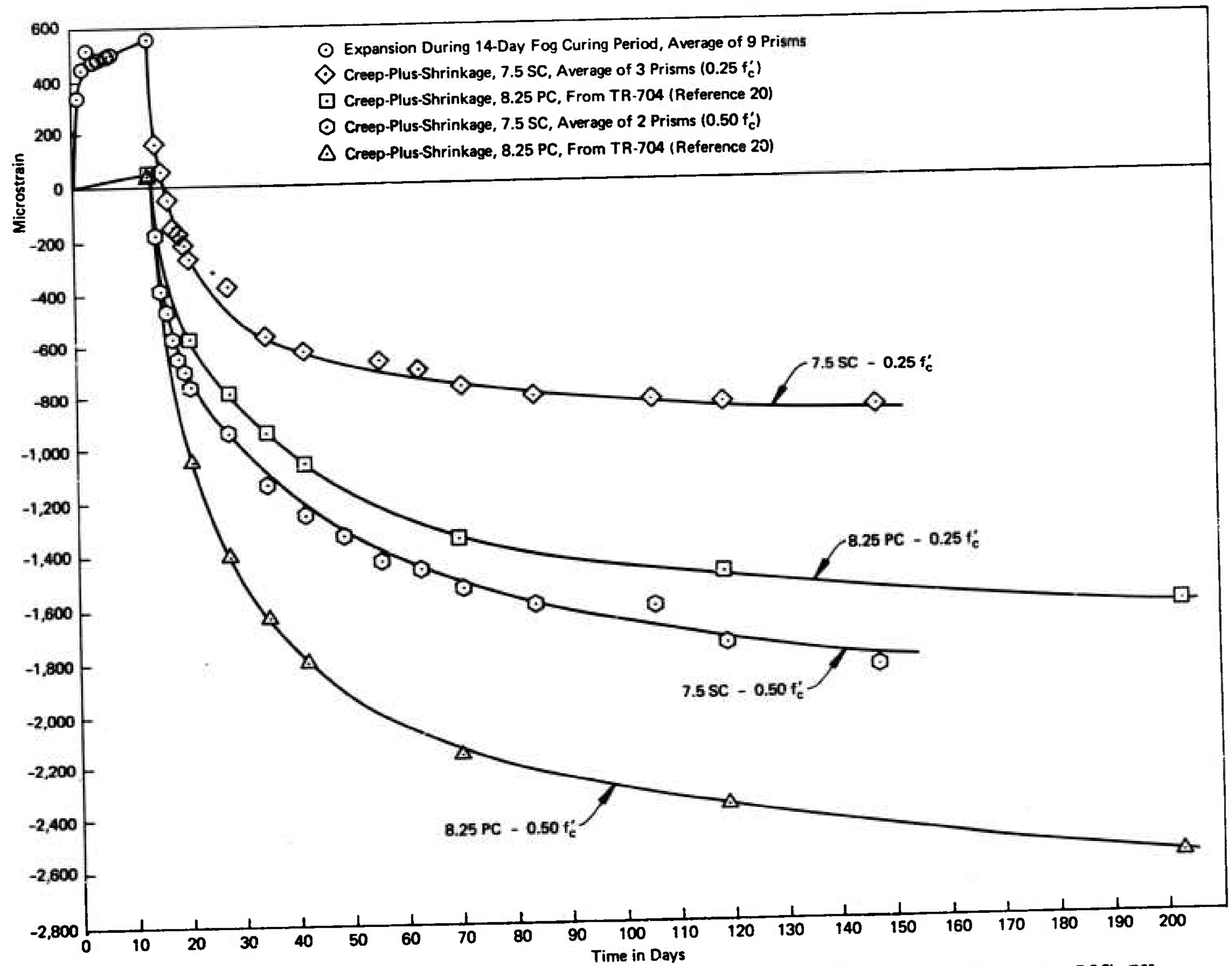
22. Effects of restraint on 14-day expansion of 1 inch by 5 inch prisms, 7.5SC.



23. Comparisons of expansion and shrinkage of 1 inch by 5 inch prisms, 25% RH, 7.5SC and 7.5PC.



24. Comparisons of expansion and shrinkage of 1 inch by 5 inch prisms, 50% RH, 7.5SC and 7.5PC.



25. Expansion and creep-plus-shrinkage of 2 inch by 5 inch prisms in 50% RH, p=0.30%, 7.5SC and 8.25PC.

REFERENCES

1. Portland Cement Association. Design and Control of Concrete Mixtures, Eleventh Edition, July 1968, pp. 12-18.

2. Czernin, Wolfgang, "Cement Chemistry and Physics for Civil Engineers," Chemical Publishing Company, 1962, pp. 1-27.

3. Klein, A. and Troxell, G. E., "Studies of Calcium Sulfoaluminate Admixtures for Expansive Cements," Proceedings, American Society for Testing and Materials, Vol. 58, 1958, pp. 989-1008.

4. Klein, A. and Bresler, B., "A Review of Research on Expansive Cement Concretes, Part I, Introduction," The Structure of Concrete and Its Behaviour Under Load, The Cement and Concrete Association, London, 1968, pp. 467-472.

5. Aroni, S., Polivka, M. and Bresler, B., "Expansive Cements and Expanding Concretes," Report No. 66-7, Division of Structural Engineering and Structural Mechanics, College of Engineering, University of California, Berkeley, California, July 1966.

6. American Concrete Institute. "Expansive Cement Concretes - Present State of Knowledge," Journal of ACI, August 1970, pp. 583-610.

7. Chemically Prestressed Concrete Corporation. Tentative Specification for ChemComp Cement, December 1968. Van Nuys, California.

8. Polivka, M. and Bertero, V., "Factors Affecting the Properties of Expanding Concrete," The Structure of Concrete and Its Behaviour Under Load, The Cement and Concrete Association, London, 1968, pp. 487-492.

9. Aroni, S. and Polivka, M., "Effect of Expanded Shale Aggregate on Properties of Expansive Cement Concrete," RILEM Symposium on Lightweight Aggregate Concretes, Budapest, Hungary, March 1967.

10. Bertero, V. and Polivka, M. "Effect of Degree of Restraint on Mechanical Behavior of Expansive Concrete," Proceedings of the American Society for Testing and Materials, Vol. 64, 1964, pp. 797-815.

11. Klieger, Paul and Greening, Nathan R., "Utility of Expansive Cement," Fifth Symposium on Chemistry of Cement, Tokyo, Japan, October 1968, also published under the title "Properties of Expansive Cement Concretes" by the Portland Cement Association R&D Laboratories, Skokie, Illinois as R&D Ser. 1370-1, October 1969.

12. Gustaferro, A. H., Greening, N. R., and Klieger, P., "Expansive Concretes - Laboratory Tests of Freeze-Thaw and Surface Scaling Resistance," Journal of the Portland Cement Association R&D Laboratories, Vol. 8, No. 1, January 1966, pp. 10-36. Skokie, Illinois (Research Department Bulletin 190).

13. Pfeifer, D. W., "Shrinkage-Compensating Concrete in Precast Wall Products," Research and Development Division, Portland Cement Association, Skokie, Illinois, March 1969 (R&D ser. 1433).

14. Aroni, S., Bertero, V., and Polivka, M., "Chemically Prestressed Concrete," Journal of the Prestressed Concrete Institute, October 1968, Vol. 13, No. 5.

15. Benuska, K. L., Bertero, V., and Polivka, M., "Self-Stressed Concrete for Building Units," Federation Internationale De La Precontrainte, Sixth Congress, Prague, Czeckoslovakia, June 1970.

16. Anon., "Instant Hotel Sets Fast Pace for Hemis-Fair Construction," Engineering News-Record, December 21, 1967, pp. 38-39.

17. Anon., "Edward Rice, Concrete's Urban Housing Pacesetter," Concrete Products, Vol. 70, No. 11, November 1967, pp. 38-39.

18. Kaiser Cement and Gypsum Corporation. Concrete Trends, Special Report T-18, May 1969.

19. Naval Civil Engineering Laboratory. Technical Report R-333-I. Study of Creep in Concrete, Phase 1 (I-Beam), by J. R. Keeton. Port Hueneme, California, Jan 1965 (AD610550).

20. ____________. Technical Report R-704: Creep and Shrinkage of Reinforced Thin-Shell Concrete, by J. R. Keeton, Port Hueneme, California, Nov 1970.